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The Mission Operations Directorate's International Space Station Alpha Hardware Familiarization Role

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The National Aeronautics and Space Administration (NASA) Mission Operation Directorate's (MOD) On-Orbit Maintenance Operations Mission Controllers are participating in space station hardware Tests and Demonstrations in multiple neutral buoyancy facilities. This is part of the controllers' hardware familiarization work in preparation to support the astronauts in the operation and maintenance of the hardware. This paper describes the larger context of Mission Controller hardware familiarization with specifics of participation in the Boeing neutral buoyancy tests. Also covered is what participation has occurred in the past and future plans.

MOD hardware familiarization as discussed in the MOD On-Orbit Maintenance Operations Support Plan is:

To develop hardware configuration expertise, the MOD personnel participate in tests and demonstrations of maintainability and maintenance procedures on mockups:

Flight Hardware Installation, Removal and Physical Integration:

-The MOD personnel observes or participates when flight hardware is installed, removed and physically integrated.

Tests and Demonstrations:

-MOD supplements knowledge of design, physical configuration, and accessibility by observing or participating in tests and demonstrations.

Photo/Video Documentation:

-MOD uses photo/video archival of flight hardware as it progresses through manufacture, integration, final assembly, ground processing and delivery to orbit in performing on-orbit maintenance and contingency repairs.

This paper was prompted by MOD's participation in the Boeing Space Station Hardware Intravehicular Activity (IVA) & Extravehicular Activity (EVA) Neutral Buoyancy Simulation (NBS) Tests at which five MOD Maintenance, Mechanical & Logistics (MM&L) Section personnel attended at various times. Specifics of the Boeing tests are used to illustrate the MOD hardware familiarization process. The MM&L participants were the author, Edward (Ted) M. Kenny, Rolunda M. McDaniel, Richard C. McKeel, Munish P. Patel, and Johnny D. Wong. The tests were at Marshal Space Flight Center, January 17 though March 4, 1994. Tests were:

IVA Hardware:

-Hatch, Common Berthing Mechanism (CBM) Controller, Crossover Rack

EVA Hardware:

-Windows, Avionics Feed Through, Water Vent, Heat Exchanger, Meteor Orbital Debris Shield, CBM.

During the EVA hardware tests some of the EVA section personnel participated. The hardware test was run under funds from the Space Station Freedom (SSF) Program and the hardware are all part of the International Space Station Alpha (ISSA).

The purposes in the MM&L personnel participation were to provide MOD on-orbit maintenance support and participation in:

Hardware Familiarization

Evaluation/Influence of Design

Maintainability/Human Factors Evaluation/Influence.

Evaluation/Influence of Maintenance & Operations Task Descriptions.

Face-to-face Interaction w/ Design Engineers

Ancillary Benefits:

-Training/Maturation

-Establish Precedent of Test/Demonstration Participation.

-Work Directly with the Flight Crew Operations Division (FCOD) (Astronauts and support personnel to the astronauts).

MM&L personnel past participation in SSF NBS tests and demonstrations were:

Rocketdyne Tests at Oceaneering:

-Electrical Power System (EPS) Robotic Interface and Maintenance Operations.

National Aeronautics and Space Development Agency of Japan Tests at Marshall Space Flight Center:

-Three week test of Restraints and Mobility Aids, Orbital Replacement Unit (ORU) Remove and Replace (R&R) and use of Power Tool.

Rocketdyne, Boeing & McDonnell Douglas Space Systems Company Tests at Johnson Space Center (JSC):

-EPS, Control Moment Gyro, and Segment Assembly and R&R tasks.

Summary of Tests:

IVA Hardware:

-About two weeks

-Boeing conducted & subjects

-Some internal suited operations

EVA Hardware:

-About five weeks:

-Three weeks Boeing conducted & subjects

-Two weeks NASA subjects (Astronauts & Flight Crew Operations personnel)

-During NASA runs some IVA operations

Live Video was Available During NASA runs and was piped back to MOD.

Fidelity:

-Mockup:

-Based on SSF design.

-Hardware still used in new ISSA design.

-Varied from very high to very low.

-Majority was moderate, some high.

-Placement of crew restraints/mobility aids was very low.

-Tools:

-Varied from very high to very low.

-Majority was moderate.

-Task Descriptions:

-Logistics Support Analysis Record Task Descriptions were used where available, Boeing test personnel wrote own if not.

-Used photos for briefing.

-As proceeded, modified procedures or allowed test subjects flexibility.

-Communication was through hydrophone (IVA) & suit system (EVA).

-Test Subjects:

-5% to 95% of Japanese female and US male respectively

-Experience - past flights (Astronauts) to none (Design Engineers, Astronauts, Neutral Buoyancy Tank personnel, Flight Crew Operations non-astronaut personnel, MOD EVA personnel, and MOD MM&L personnel)

The tests were used or resulted in confirmation or modification of operational and maintenance activities and the design of hardware, tools, and support equipment.

The evaluations of the operational and maintenance activities and the design were based upon the following factors:

-Human factors

-Safety

-Accessibility

-Quality of task instructions

-Quality of design

Using the design engineers and the operators in the actual tests resulted in very little resistance to recommended changes in the equipment or operational and maintenance activities.

MOD Benefits Summary:

Passed information to others within MOD, FCOD, Program Office, Engineering, Etc.) through one-on-ones, briefings, presentations, systems briefs, etc.

Became familiar with hardware.

Evaluated/Influenced tool and equipment design.

Evaluated/Influenced system and maintenance operations task descriptions.

Conducted face-to-face discussions with design engineers.

Personnel received training/ maturation.

Reestablished precedent of test/demonstration participation.

Worked directly FCOD Astronauts and support personnel.

Participated as test subject.

Future plans:

Participate in Future ISSA Tests, Demonstrations, Installation & Integration Operations, and Photo/ Video Documentation.

Provide test subjects.

Conduct tests.

Since the Boeing NBS test and because of the good results, experience and the recommendations from the MOD's MM&L personnel' participation in the tests; there have been other tests and demonstrations that MM&L has supported. A few of these tests/demonstrations and they results/uses are:

An MM&L personnel (Johnny D. Wong) initiated an ISSA Tool Fit Check on a Thermal Control System(TCS) pump package mock-up. The test indicated that a 10" 3/8" drive extension should be added to the Standard IVA Tool List. A reach of 20" is required to remove the mounting bolts on the pump package. Current tools on the IVA

Tool List do not facilitate this reach.

MM&L personnel (Mona Mangal and Rolunda M. McDaniel) participated in the EVAS5 WETF Tests with astronaut crew members. The rigid tether operation and Payload ORU Accommodation (POA) Latching End Effector (LEE) were evaluated. The primary objectives of the test were reach and access evaluation and resulted in recommended design changes.

An MM&L personnel (Mark T. Davison} lead a Detailed Test Objective (DTO) 668 Advanced Lower Body Rèstraint Test (ALBRT) training (in the CCT) for the STS 66 crew. The DTO is designed to provide the crew member lower body support during RMS and Camera Operations. The Restraint is attached to the Aft Flight Deck Panel and at the ISSA robotic work station site.

Biography: Mr. Zingrebe is a SOLE Life Member and member of National Council on Systems Engineering, Alpha Pi Mu, and Phi Kappa Phi.

Mr. Zingrebe is a Barrios group lead in the Johnson Space Center, Mission Operations Directorate, Space Station Systems Division, Environmental Systems and Maintenance Branch.

Mr. Zingrebe's fields of experience include Systems Engineering, Integration, Design, and Modeling; Production, Maintenance, and Facilities Engineering; Aerospace Operations and Development; Integrated Logistics Support; University Instruction; and Consulting.

Mr. Zingrebe has worked for or on projects for Barrios Technology; Rockwell Space Operations; NASA; SOFEC Defense Systems; Navel Facilities Engineering Command; BDM; U.S. Army, TCATA; U.S.A.F., Range Applications Joint Program Office, Ballistic Missile Office, Institute of Technology, and Office of Scientific Research; TRW; General Motors Defense Systems; U. of Houston, Industrial Engineering, Operations Management, and Hilton College of Hotel and Restaurant Management; U. of Texas, School of Nursing; and Clorox Co.

Mr. Zingrebe has an M.B.A., Operations Management; M.S. and B.S., Industrial Engineering; from the University of Houston and a B.S., Packaging Engineering from Michigan State University

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Alternative Approach To Vehicle Element Processing

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ABSTRACT

The National Space Transportation Policy (NSTP), dated August 5,1994 best describes the challenge facing today's aerospace industry. "Assuring reliable and affordable access to space through U.S. space transportation capabilities is a fundamental goal of the U.S. space program". Experience from the Space Shuttle Program (SSP) tells us that launch and mission operations are responsible for approximately 45 % of the cost of each shuttle mission. Reducing these costs is critical NSTP goals in the next generation launch vehicle.

Based on this, an innovative alternative approach to vehicle element processing was developed with an emphasis on reduced launch costs. State-of-the-art upgrades to the launch processing system (LPS) will enhance vehicle ground operations. To carry this one step further, these upgrade could be implemented at various vehicle element manufacturing sites to ensure system compatibility between the manufacturing facility and the launch site. Design center vehicle stand-alone testing will ensure system integrity resulting in minimized checkout and testing at the launch site. This paper will addresses vehicle test requirements, timelines and ground checkout procedures which enable concept implementation.

INTRODUCTION

Current funding levels associated with the nation's launch systems (expendable and man rated) have brought about an increased interest in the probability of launch (POL) and life cycle costs (LCC) associated with current and proposed launch programs. High recurring SSP costs have been attributed to the "standing army" at the launch site who support vehicle ground turnaround operations. It should be noted that the cost breakdown from SSP cost-per-flight data, NASA FY'94 budget inputs to the Office of Management & Budget, does not support these beliefs. Of the dollars spent on each launch, 27 % is attributed to vehicle ground operations at the John F. Kennedy Space Center (KSC), see Figure 1.

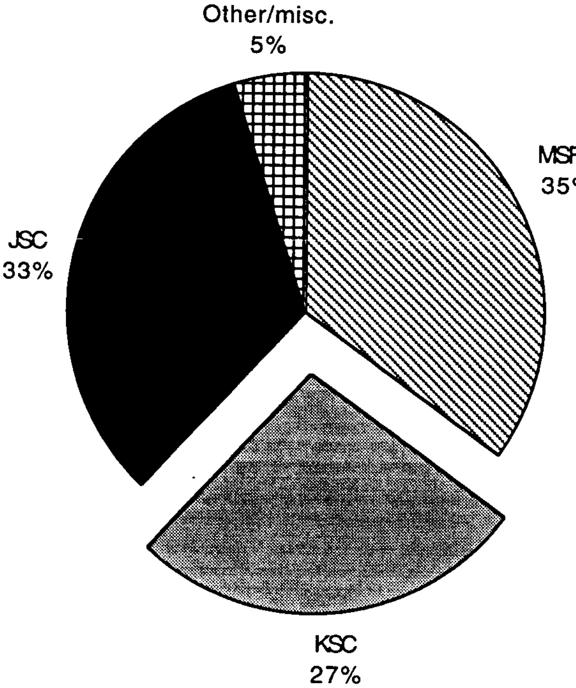

Figure 1. STS Cost Per Flight By NASA Center

The SSP budget at KSC is distributed in eight categories. While the largest portion of the center's budget is allocated for hands-on element processing, it should be noted that approximately 42% is spent on support activities. The allocation of SSP funds at KSC is illustrated in Figure 2.

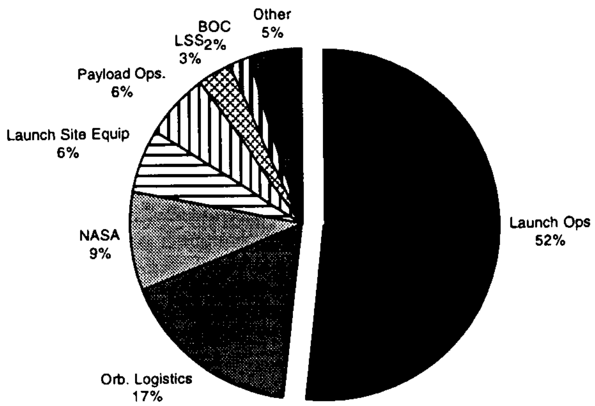

Figure 2. KSC Funding By Category

SPC funds are subdivided to encompass major functions performed in support of SSP operations. remainder being allocated to support functions. Of the SPC funds, approximately one third is devoted to hands-on processing activities with the remainder being allocated to support functions. This is illustrated in Figure 3.

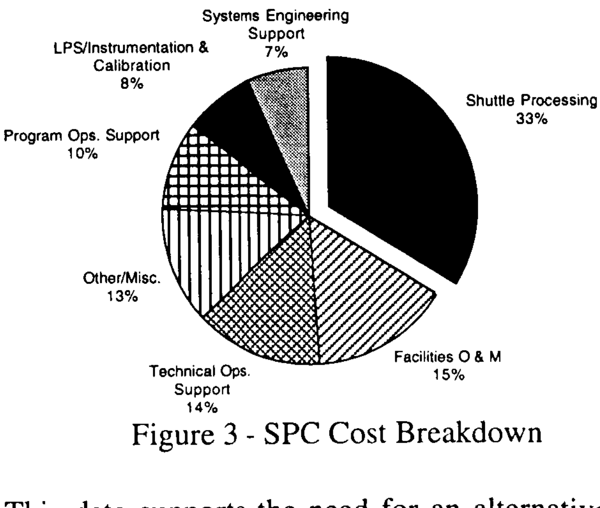

Figure 3 - SPC Cost Breakdown

This data supports the need for an alternative processing approach which extends to all centers thereby reducing overall program LCC by use of built-in efficiencies which reduce the number of requirements during each step in preparation for launch. SPC data indicates that a typical STS flow, includes six thousand Operations and Maintenance Requirements & Specifications (OMRS) which must be satisfied. A cultural change in vehicle testing philosophy must be introduced to minimize these requirements. This cultural change must reduce requirements that drive both integrated factory and launch site processing.

BACKGROUND

The reduction of hands-on processing activities can be best accomplished through the reduction of ground checkout requirements. While the reduction of processing requirements sounds simple, the level of confidence in the vehicle's ability to safely achieve mission objectives must be maintained. The requirements document details procedures that must be performed and the frequency of performance in the ground processing/testing sequence. In order to satisfy vehicle design criteria have been met and insure the vehicle has been properly tested, all requirements must be documented prior to launch.

The number of test procedures performed for each vehicle turnaround determines the amount of schedule time required for the processing of these space vehicles prior to launch. In the case of the STS many of these requirements are duplicated at both the design center/manufacturing facility and again at the launch site because the test programs and test equipment at these respective facilities are not compatible. The performance of redundant testing results in the escalation of the LCC of these launch programs. The Integrated Factory/Launch Site Processing Concept identifies & reduces these redundancies while satisfying vehicle design criteria and ensuring the level of confidence required at the launch site.

Our studies assessed vehicle processing of several launch programs (both manned & unmanned) which included Saturn/Apollo, Shuttle, Delta and Titan IV. This analysis revealed that in each of these programs much of the factory testing is repeated at the launch site. There were several reasons for this as listed below :

- Vehicles are shipped short of equipment to meet schedule constraints.
- Manufacturing completion/vehicle integration is performed at the launch site.
- Modification kits are installed at the launch site resulting in system retest.
- Additional testing at the launch site creates a sense of improved reliability.
- Maintenance is performed on reusable vehicles at the launch site.

These reasons were common to all the programs we analyzed. This suggests that a processing concept which minimizes the time required at the launch site for ground test activities of both manned and unmanned programs is desirable. In order for this to happen several things must occur :

- Vehicle elements must be completely assembled at the factory (No assembly operations are deferred to the launch site).
- Factory testing is not deferred to the launch site.
- Modification kits are not installed at the launch site.
- Factory and launch site personnel require access/input to factory test procedures. The launch site must have connectivity to the factory and be able to transfer design/build/ test data electronically for use in verification testing at the launch site.
- Multiple database access is implemented to allow both manufacturing and launch site personnel to share data with each exchanging their "viewpoints".
- A system environment which allows for end user configuration which links multiple locations.
- Factory and launch site checkout procedures and associated software must be similar if not identical. This is imperative in adopting the Integrated Factory/Launch Site Proçessing Concept.
- Vehicle design reflect maintainability influ ence including selective operation of redun dant systems during the mission.

Implementation of this processing concept is reduced LCC associated with vehicle testing which equates to reduced costs per pound of payload to orbit. In order to financially compete in the international aerospace marketplace this concept must be achieved.

APPROACH

Our initial studies into the Integrated Factory/ Launch Site Processing Concept began in 1990 with the selection of a vehicle configuration. The most applicable data which was currently available at the time was STS related. This reason, coupled with the fact that Shuttle-C was the current NASA concept for a heavy lift launch vehicle (HLLV) resulted in the selection of a side mount shuttle derived vehicle (SDV). The SDV (FIG 4) is made up of the following elements :

- Side Mount Unmanned Cargo Carrier (new element)
  - STS boattail
  - STS based MPS
  - STS based APS
  - Single fault tolerant avionics system
- External Tank (STS specifications)
- Solid Rocket Boosters (STS specifications)

For the purposes of this study we felt the SDV would make maximum use of STS resources & technologies and effective comparisons could easily be made between the two. In addition the SDV would be capable of: a) utilizing existing KSC facilities with little to no modifications, b) STS ground processing procedures with minor revisions, c) STS databases and d) accommodate orbiter payloads. While this study focused on a side mount SDV, the concept is directly applicable to the current RLV concepts.

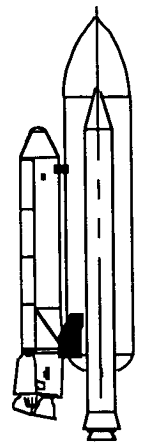

Figure 4. SDV Configuration

After configuration selection, the STS OMRSD was analyzed for multiple systems which were common to both STS and SDV. The selected systems were :

- Auxillary Power Unit (APU)
- Communications & Tracking (C&T)
- Data Processing
- Electrical Power Distribution & Control (EPD&C)
- Flight Controls
- Guidance, Navigation & Control (GN&C)
- Hydraulics
- Main Propulsion System (MPS)
- Operational Instrumentation (OI)
- Purge Vent & Drain (PV&D)
- Reaction Control System (RCS)

For each of these systems an analysis of the OMRSD and the Operational & Maintenance Plan (OMP), which tracks OMRSD status, was conducted. The OMRS and OMP were used because these documents are a) current, b) readily available and c) applicable to SDV.

At this point it should be noted that OMRSD and OMP requirements with an effectivity other than those for first vehicle flow or all vehicle flows were not considered since they are not applicable to SDV. From this analysis, it was also determined where the OMRSD/OMP requirement was satisfied (factory, launch site or both). For each requirement satisfied at the launch site the Operational Maintenance Instruction (OMI) was noted and documented. The OMI is the detailed planning/work document for test and maintenance activities used at the launch site. Matrices were developed cataloging data for each of the systems listed:

- OMRSD requirement number
- Title
- OMI number and sequence

An analysis of the Test Requirements Specification Document (TRSD) was initiated. The TRSD defines the work required at the manufacturing facility in the construction of a new vehicle. Using data acquired from the manufacture of OV-105 (Space Shuttle Endeavour), we were able to determine the TRSD equivalent to the OMRSD where applicable. For each TRSD equivalent requirement the implementing Test Checkout Procedure (TCP) was identified. TCP's are used at the manufacturing facility to direct manufacturing test procedures - TCP's & OMI's are similar in nature with the major difference being the location at which they are performed.

Once all this data was collected the OMRSD/OMP matrices were expanded to include the following information :

- TRSD requirement number
- TCP number and sequence
- Remarks

From these matrices a master matrix which documented the total test requirements to be satisfied for a ground processing flow was developed. An analysis of this matrix substantiated our belief that a high degree of redundancy existed in the testing performed at both the manufacturing facility and the launch site.

Following this analysis of the OMRSD/TRSD data, the next step was to determine the amount of time spent on test procedures utilized at both the manufacturing facility and the launch site. Once this was determined the next step was to highlight the non-equivalent items and the duplicative testing which occurred. From this we were able to calculate timelines for each of these items as well as the time required to run a complete checkout at the manufacturing facility.

Timeline development for each of the systems previously discussed was achieved in one of three methods :

- Use of timelines contained within the individual OMI's where available
- Use of as-run timelines where available
- Use of manufacturing timelines from Space Shuttle Endeavour

Timelines which are contained within the OMI's are an estimate of the time required to run a complete procedure. OMI as-run timelines can either be for a complete procedure or any number of sequences from the procedure; however, as-run data gives a more realistic insight into the actual time required to complete the procedure and allows for more representative schedule forecasts. Timelines acquired from the manufacture of the Space Shuttle Endeavour used both estimated and as-run data.

For this effort it was necessary to determine which sequence(s) of the OMI were required to satisfy the OMRSD requirements. When this had been determined, timelines were redlined to ensure that only the required sequences of the OMI were incorporated into the revised timelines. Throughout this area of our studies we focused on reducing launch site activities without jeopardizing the integrity of the launch vehicle. One reason for this is when the vehicle is tested at the manufacturing facility a small contingent of personnel supports this testing. At the launch site the infrastructure required to support vehicle testing is broader in scope and therefore is more costly. Also, manufacturing operations are run on a 2 shift per day work schedule while the launch site utilizes both 2 & 3 shifts per day. These reasons alone support the transfer of test activities from the launch site to the manufacturing facility.

Based on our analysis of the OMI/TRSD data and the timelines which were developed we were able to look at the Integrated Factory Timeline and determine which redundant testing could be transferred from the launch site to the manufacturing facility. This resulted in a longer test program at the factory; however, the horizontal turnaround activities at the launch site were reduced from approximately seventy days to nine days. Figure 5 shows the manufacturing test timeline for the recently completed Space Shuttle Endeavour and projected timelines for the manufacture of the SDV which includes testing transfered from the launch site to the manufacturing facility. The difference is neglible while the savings at the launch site is significant. It should be noted that these savings can only be realized if the guidelines listed earlier are adhered to.

GROUND CHECKOUT SYSTEM CONCEPT

A launch processing system concept that enhances the inter- and intra- operability between launch site and manufacturing processing was developed. The launch processing requirements were based on specifications from LPS upgrades at KSC. To achieve the goal of reducing launch site activities by enhancing the commonality with the manufacturing process, the following items were assessed in the determination of the system architecture requirements :

- Common checkout philosophy (factory/ launch site)

- Common checkout equipment
- Common ground software
- Launch site input to factory checkout
- Launch site real-time monitoring/control

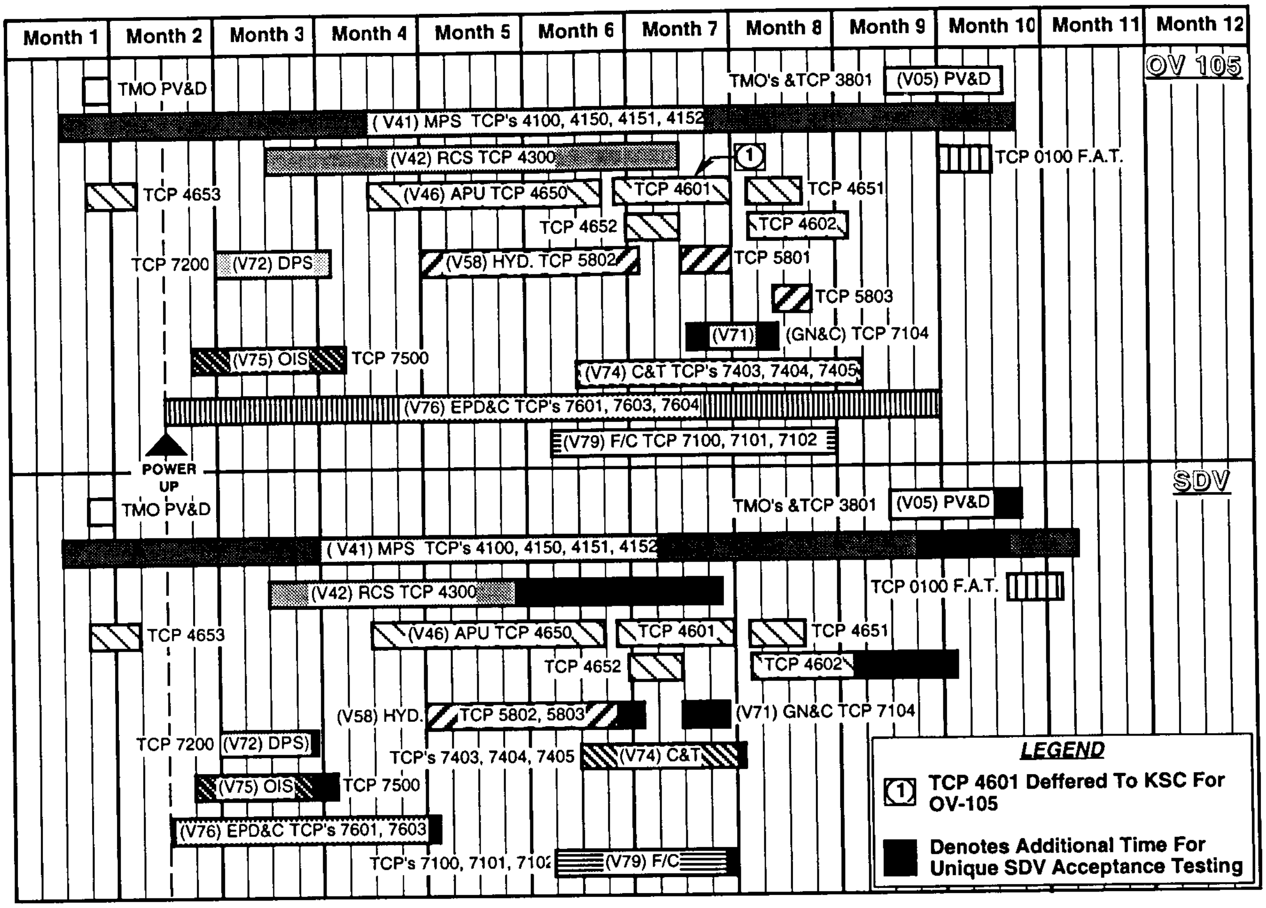

Figure 5. Integrated Factory Checkout Timeline

This architecture incorporates the concept of a ground infrastructure data/communications link in which manufacturing and launch site personnel can be electronically linked as illustrated in Figure 6.

With this architecture, factory and launch site personnel are able to have access/input capability to test databases, real-time test support, post-test anomaly resolution and verification testing. Multiple databases and their access will be implemented in a way that allows for manufacturing and launch site personnel to share data with each having their own "viewpoint". This allows the vehicle idiosyncrasies, failure flags and failure trend analysis to be easily accessible by either manufacturing or launch site personnel.

A system environment that allows for an end-user configuration that is linked with multiple locations was a prime criteria. This is necessary to allow for the incorporation and redistribution of equipment necessary to execute test sessions by multiple factions. This environment has to be capable of accommodating application software that can be executed in multiple locations based on system throughput or the time critical nature of the data that is being generated and recorded. To incorporate these diverse criteria a distributed environment is needed that is transparent at the application, user and network level.

A user environment needs to be able to operate in

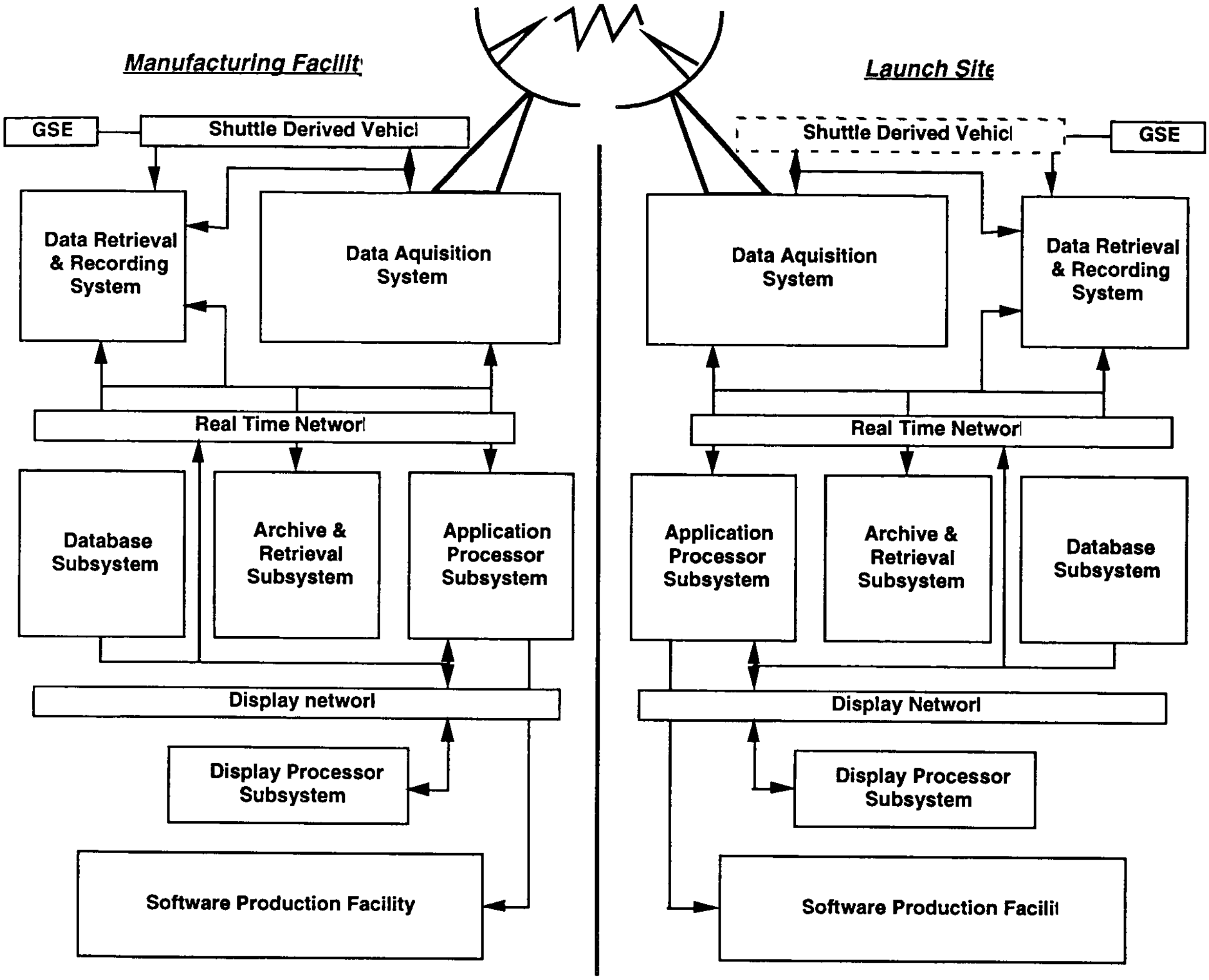

Figure 6. Ground Checkout System Concept

a consistent fashion over multiple platforms to allow for high resolution graphical display and character based consoles where appropriate. This will keep costs in proportion to task utilization. Training costs and associated overhead will be reduced especially in high turnover positions or with a vast number of users. In addition, person nel will become more productive and confident in the production of their tasks. One way to enhance this criteria is to provide a consistent user interface that provides help checks for potentially disastrous commands, resolves conflicts, brings conflicts to the user's attention and automates tedious lengthy commands. This interface must also be capable of execution on multiple platforms without multiple user interfaces.

SUMMARY

Ground processing costs can be significantly reduced by adopting this concept. It should be noted that a paradigm shift must occur within the aerospace community (private sector & government) in order to implement this concept. Use of the concept will reduce the number of induced failures which have occurred at the launch site during STS testing. Using data from testing at the manufacturing facility, launch site personnel can develop a knowledge base for each vehicle which can be used at the launch site during acceptance testing to verify that the thresholds levels which were recorded during manufacturing tests have not changed during transportation and handling.

Test personnel at both sites are able to interface with the system and display data in recognizable formats which reduces training requirements. Precedence for this concept exists in the form of the planned STS launches from the Vandenberg Launch Site. In addition to reduced LCC associated with ground testing, there is a savings to be gained from reduced facility complexity. The goal is to adapt this concept to the RLV program. A major criteria of the RLV program is to provide a launch vehicle which is both operable and dependable while minimizing program LCC. Preliminary results indicate that the application of the Integrated Factory/Launch Site Processing Concept can be readily applied to the RLV program and be instrumental in achieving NSTD goals.

HUBBLE SPACE TELESCOPE - FIRST SERVICING MISSION
"Down to Earth Logistics - From GSFC to KSC and Back"

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Abstract

The Hubble Space Telescope First Servicing Mission is a major accomplishment for NASA and has drawn world-wide attention and interest. The extravehicular servicing and repair activities performed by the STS-61 crew were the most ambitious ever undertaken. Their unprecedented success in performing on-orbit repair and maintenance, particularly in correcting the aberration in the primary mirror, has enabled the HST to provide sensational images and the anticipation of exciting scientific discoveries. Although the whole world watched the televised logistics activities (on-orbit maintenance) that took place in space, few are aware of the time and effort that went into planning and executing the space logistics that takes place with our feet on the ground. This paper addresses a major part of that effort - the Packaging, Handling, and Transportation (PH&T) activities required to ship the GSFC HST space flight hardware and ground support equipment to KSC for launch and the post launch return to GSFC. It addresses the logistics and transportation planning for the containers for the Solar Array Carrier, the Orbital Replacement Unit Carrier, and the Flight Support System and their transporters, and the over land and water portions of the shipments.

Introduction

In December 1993, millions of people around the world watched their television sets as astronauts of Space Shuttle Endeavour, STS-61, carried out NASA's most ambitious and longest duration servicing mission, the repair of the Hubble Space Telescope (HST). The success of this mission is now history. The solor arrays and miscellaneous Orbital Replacement Units (ORUs) were replaced. The Hubble's most notorious problem, blurred images caused by a flawed mirror, was corrected by installation of the Corrective Optics Axial Replacement (COSTAR) and a modified Wide Field/ Planetary Camera (WF/PC). Scientists now delight in the knowledge of the clear images and data being provided by the refurbished and repaired HST.

Logisticians can take great pride in the success of the on-orbit maintenance and servicing of HST and the engineering, planning, and execution by the "logisticians" of the HST team. As any logistician can tell you, Maintenance Planning is a primary element of logistics. The HST was designed and built to be maintainable, serviceable, and refurbishable on orbit. It was designed for supportability - a goal for which logisticiains continuously strive. The success of the HST First Servicing Mission focused attention on "space logistics" or the logistics of supporting systems in space. However, contributing to the HST success were other logistics efforts that were not nearly as glamorous, nor attention getting, as the activities in space. These efforts were the logistics activities that took place in support of the mission with our feet on the ground - the Packaging, Handling & Transportation (PH&T) of the HST flight hardware and support equipment prior to and post launch. The "logistics in space" has received the attention and recognition it rightly deserves. This article will focus on the "earthy" logistics of the planning and effort required to safely deliver the flight hardware and support equipment required for the mission from the HST project test and integration site at Goddard Space Flight Center (GSFC), Maryland, to the launch site at Kennedy Space Center (KSC), Florida.

The Team

Responsibility for mission planning, engineering, and test and integration of flight hardware and support equipment resides with the HST Project Office/Code 442 which is located at GSFC in Greenbelt, Maryland. The Logistics Management Division/Code 230 at GSFC provides the HST Project with logistics expertise and resources required to support the HST servicing missions.

The Hardware

The First Servicing Mission called for various activities as replacement of components and ORUs such as the Gyro Electronic Control Units, Magnetometers, and Solar Array (SA) Drive Electronics (SADE). Other major activities were the replacement of the SA and installation of the WF/PC II and COSTAR. As well as the flight hardware to be replaced or installed, the First Servicing Mission (FSM) required various items of flight support equipment to transport the flight hardware in

the Endeavour bay to the HST and to assist in the servicing operations. The principal pieces of Flight Support Equipment (FSE) were the:

a) Flight Support System (FSS)
b) Orbital Replacement Unit Carrier (ORUC)
c) Solar Array Carrier (SAC)

The FSS is the approximately fifteen foot diameter ring mounted in the rear of the shuttle bay. The astronauts capture the HST with the Remote Manipulating System (RMS) robot arm and secure it to the FSS and shuttle, providing a stable platform for HST servicing activities.

The ORUS is a cradle housing the ORUs and tools for the mission and is positioned in the shuttle bay in front of the FSS. The astronauts remove the "new" ORUs from the ORUC for installation into the HST and place the "old" ORUs into the ORUC for return to earth.

The SAC is a platform positioned forward of the ORUC in the shuttle bay and is used in a similar fashion for the solar arrays as the ORUC for ORUs. Because of difficulties during the actual mission, one of the solar arrays was cast off into space instead of being fastened to the SAC for return to earth.

In addition to the Flight Hardware and FSE, Ground Support Equipment (GSE) was required to be shipped from GSFC to KSC in support of the mission. Although

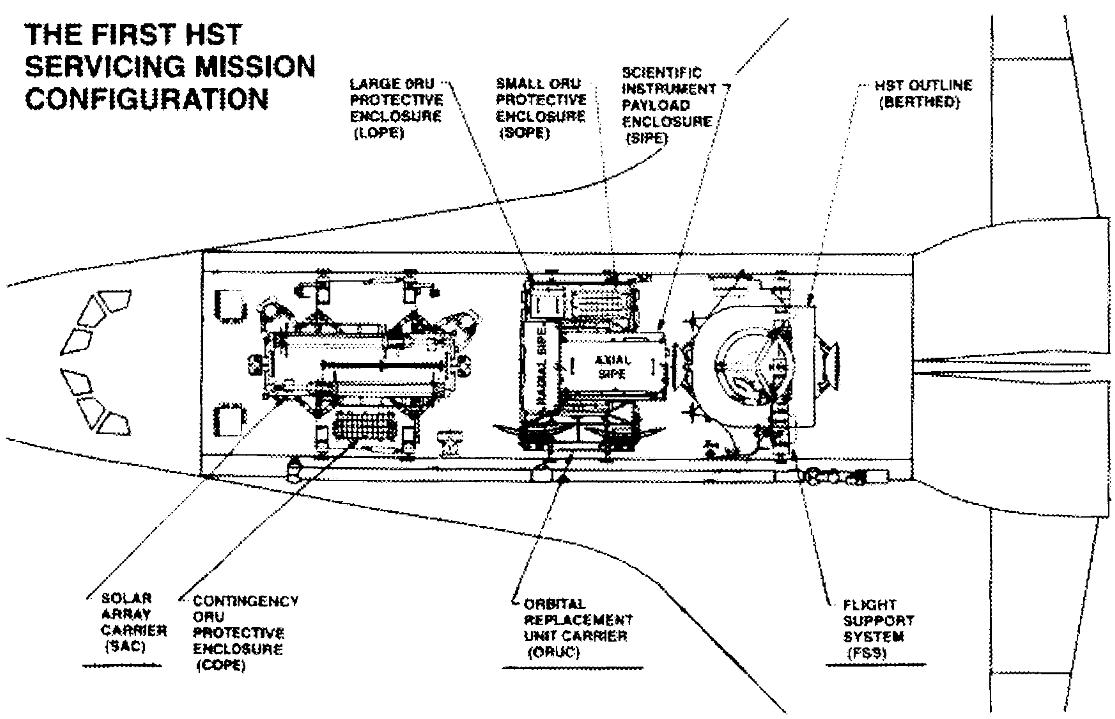

Fig. 1 Endeavour's cargo bay showing the Solar Array and Orbital Replacement Carriers and the Flight Support System.

the GSE required over twenty tractor trailers for shipment, it was the transportation of the Flight

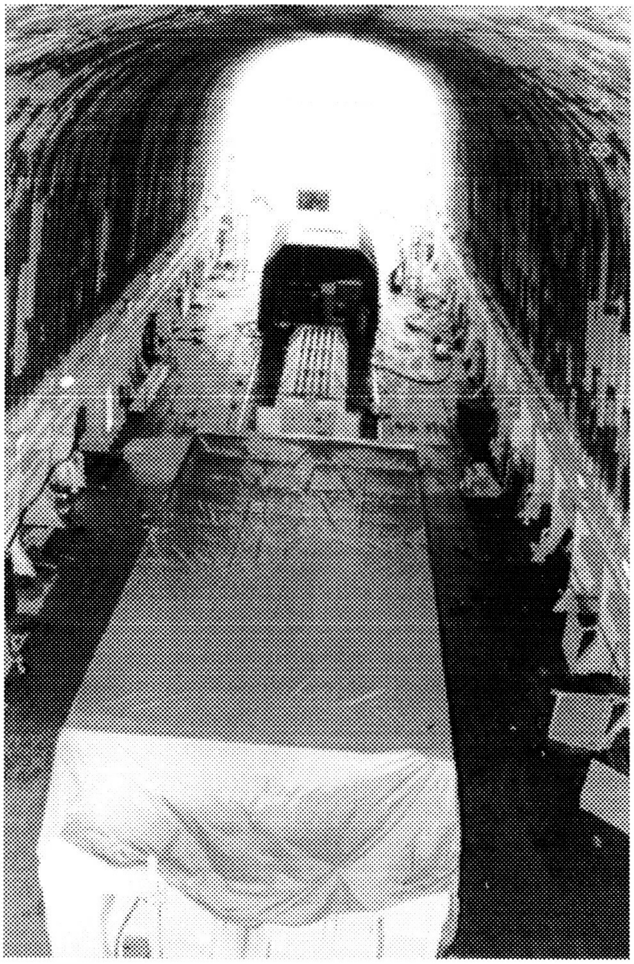

Fig. 2 The LDEF, Tube Truck, & GRO Transporters on ET Barge.

Hardware and FSE that provided the greatest logistics challenge and required the most planning and effort by the engineers and logisticians.

The Challenge

Logisticians from the Logistics Management Division/ Code 230 worked with the HST Project Office/Code 442 engineers to conduct transportability analyses, identify and evaluate alternatives, conduct feasibility studies, evaluate container designs, prepare cost analyses, recommend modifications, identify potential contractor capabilities, prepare transportation plans, and coordinate logistics activities. A Space Support Equipment Logistics Working Group (SSELWG) was created and chaired by the HST Project Carrier Manager to foster communications, maintain schedules, interchange information, and manage the myriad of details and activities required to plan and execute the movement of the flight hardware to KSC. The challenge facing the SSELWG was to identify and satisfy the requirements for economically and safely transporting program critical space flight hardware and FSE from GSFC to the launch site.

The Requirements

The major pieces of FSE, the FSS, ORUC, and SAC, require environmentally controlled containers for shipment. These pieces of FSE are also relatively large, about fifteen feet across the trunion supports, and consistent with the inside dimensions of the shuttle bay. Therefore, relatively large containers had to be sought that could be environmentally controlled and capable of being transported over the road, since GSFC has neither an airfield nor waterfront. Two major alternatives for container/transporters were considered. Existing container/transporters were sought that could be modified to satisfy HST's requirements and the feasibility and cost of building new container/ transporters were assessed. Looking for existing containers was the first choice. Standardization, multi-purpose, reutilization, recycling, cost avoidance, least life-cycle cost, etc. are all buzz words the logistician is familiar with and using an existing container would appear to provide the most benefit.

The Solutions

GSFC had a container that was built for another of its spacecraft, the Compton Gamma Ray Observer (GRO), that appeared to have potential for reuse. The GRO container/transporter was stored in the vicinity of KSC awaiting disposition decision. Since GRO was a shuttle payload, the internal dimensions of the container would be suitable for HST hardware. The GRO was transported by C-5 aircraft so it was obviously air transportable. However, the GRO was shipped from one airfield in California to another at KSC and over public road transport was not a consideration. The roller flatbed that was part of the GRO container/ transporter was about five feet high and was used as a loading platform for the C-5 aircraft. Its transport purpose was for short run, slow speed, surface transport from manufacturer's plant to aircraft and from aircraft to launch processing facility. It was not intended to be an over road transport trailer for the GRO. The 5 ft. added to the 13 ft. height of the GRO container made the container/transporter over 18 ft. tall and much too high to pass under the overpasses in the GSFC area and get from or to Andrews AFB, Maryland, the nearest C-5 airfield. The height problem was readily overcome by being able to use a double-drop low-boy trailer that Code 230 had procured for transporting other GSFC payload containers. The new trailer was only 2 ft. high and loaded with the 13 ft. GRO would make a total height of 15 ft. which could pass under most of the overpasses in the GSFC vicinity. The height problem was solved, but then there was another formidable problem with the width. The GRO container was 18 ft. wide. Sixteen feet is the maximum width Florida will allow with a waiver to their restrictions for use on their roads. Some of the other east coast states won't even allow 16 ft. The width of the GRO, being an insurmountable problem, meant that if used, it would have to be restricted to transport by air or by water. The State of Maryland would allow over the road movement of the 18 ft. wide GRO from the airfield at Andrews AFB, or the Baltimore/Chesapeake Bay waterfront, to GSFC. At this point HST knew it had a container that could be used for air or water transport of at least one of its three pieces of flight hardware. All that had to be done was get it from KSC to GSFC. A USAF C-5 mission to transport the GRO from KSC to Andrews AFB would cost about $100,000, not including the $3,000 for rigging to get the GRO off the roller bed and on to the low-boy and then the escorted convoy over road movement to GSFC. These transportation costs now added new factors to the container/transporter decision process. When the cost of transport of the GRO starts to approach what it might cost to build a new container for perhaps more than one item, maybe it is not more cost effective, nor the wise decision, to reuse the old.

While the logisticians and engineers were pondering the pros and cons of using the GRO container/transporter for one piece of flight hardware, they were also trying to determine what to do about the other two pieces. Estimates to build new containers ran from $150,000 to over $1 million, with varying schedule and technical risk factors to be considered and evaluated. The search for container/transporters already in existence continued with most being eliminated as not large enough to suit the HST needs. As well as GRO, there was another large container/transporter at KSC. This one belonged to Langley Research Center(LaRC) and was used to transport the Long Duration Exposure Facility (LDEF) from LaRC to KSC. The LDEF was to be recovered from orbit by the shuttle and returned to earth. The LDEF container/transporter would be required to return the LDEF to LaRC. The GSFC team contacted LaRC and determined that the LDEF had potential and might be made available to GSFC. After numerous technical interchanges, engineering analyses, and drawing reviews, it was concluded that the GRO container would carry the SAC with only minor modifications to the trunion supports. It was also determined that the LDEF container, with more extensive modification, could carry both the ORUC and FSS. Technically, HST had a handle on resolving its container/transporter problems. The logisticians attached the logistics problems associated with the economical movement of such large container/transporters.

The Modifications

The LDEF was designed to be transported by barge and because of the inadequacy of its running gear and like GRO, its size was not suited to over road travel. The LDEF was towed slowly from LaRC to the waterfront at Langley AFB where it was loaded on a barge for shipment to KSC. Neither at LaRC, nor KSC, did the LDEF have to travel on public roads or pass under any overpasses, so its height and size presented no problem. Unlike GRO, the LDEF container could not be removed from its transporter/trailer. The container was structurally an integral part of the trailer and could not be removed and placed on a low-boy trailer. The LDEF, with its domed roof was about 18 ft. high and at that height, even with waivers from Maryland for over road movement, would not be able to pass under the overpasses between the Chesapeake waterfront and GSFC. To be able to get the LDEF container to GSFC, it was decided to have it modified at LaRC. Codes 442 and 234 worked with LaRC to identify, select, and award a contract to a fabricator in the LaRC area to modify the LDEF container/transporter for the HST ORUC and FSS.

The LDEF was returned to LaRC and the selected contractor by the same mode that it was brought to KSC, by barge. The NASA External Tank (ET) barge ferried the LDEF from KSC to LaRC. Code 230 negotiated with LaRC and Marshall Space Flight Center (MSFC), the owner/operators of the ET barge, to transport the GRO along with LDEF. This got GRO to Virginia, avoiding the expense of a C-5 flight. LaRC stored the GRO container/transporter until the modifications to the LDEF were completed and then both LDEF and GRO were shipped by barge to GSFC. LaRC worked with GSFC to oversee the contractor's completion of the modifications. The running gear of the trailer was replaced with one that would satisfy Department of Transportation (DOT) requirements for over the road use. Air bags were installed to provide air-ride shock absorption for the payloads and the capability to raise or lower the height of the container to pass under overpasses. The domed roof was replaced by a flat one which reduced the height of the LDEF to between approximately 15 and 16 ft., depending on the inflation of the air bags. Trunion support structures were constructed for the FSS and ORUC and new external container walls were built. The Environmental Control System (ECS) was also modified and adjusted for HST requirements. When the modifications were complete, Code 230 executed their transportation plan for shipping both LDEF and GRO by barge from LaRC to GSFC.

Transportation of Container/Transporters to GSFC

At LaRC the GRO container was removed from the roller bed trailer upon which it had been shipped from KSC and positioned on the double-drop low-boy provided by Coce 230 for over road transport. The LDEF and GRO container/transporters were towed from LaRC across the Langley AFB runway to the waterfront where a commercial shallow water barge and tug awaited. Since a prepared pier/dock was not available, Code 230 arranged for a commercial rigger to construct a loading area/ramp from the shore to barge, enabling the transporters to be backed onto the barge by the tractors. The tug captain held the barge in place with the use of the tug's engines until loading was complete. The barge was then towed up the Chesapeake to the Defense Logistics Agency Depot waterfront area at Curtis Bay, just south of Baltimore. After off loading at Curtis Bay, a convoy of the transporters, commercial tractors, support equipment trucks, government, commercial, and DOT escort vehicles, and local and state police, was formed for the over road trip to GSFC. The convoy could not depart until after midnight to comply with the Maryland permit restrictions for the movement. Upon arrival at GSFC, the container/transporters were positioned in the vicinity of the space flight hardware for Environmental Control System (ECS) testing and future loading of the flight hardware for shipment to KSC. The movement of container/transporters by barge and over the road from LaRC to GSFC served to provide logistics planners with a "dry run" of the transportation concepts they planned to utilize for the HST First Servicing Mission. All went successfully as planned.

Transportation of Mission Hardware to KSC

ET Barge. Code 230 arranged with MSFC for the HST flight hardware container/transporters to be transported from Curtis Bay, Maryland, to KSC by the NASA ET barge. The shipment dates were coordinated with MSFC to coincide with the shipment of an ET to KSC from Michaud, Mississippi. This coordination enabled the HST project to pay for bringing the barge to Curtis Bay only from KSC and not the leg from Michaud. Code

Fig. 3 The ET Barge leaving Curtis Bay, Maryland.

234 also coordinated with the U.S. Coast Guard to be sure that the Chesapeake bridges could be opened and that there would be no impediments to the travel of the barge up the Chesapeake. Even with this prior coordination and Coast Guard assurances, a contractor

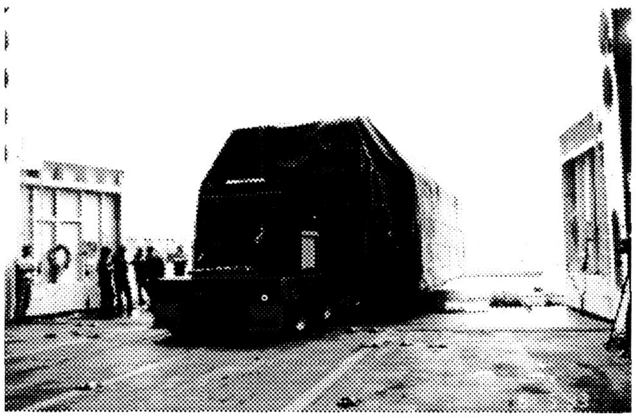

Fig. 4 The GRO Transporter being off loaded at KSC.

painting a draw bridge left one of his barges tied on one side of the span, leaving insufficient room for the ET barge to pass safely. The ET barge, being 40 feet high and 200 feet long, acts as a sail in the wind and can be difficult to control in the narrow channels of the bay. Fortunately, the construction paint barge was removed without causing mishap to the ET barge and only minimally effecting the schedule. The positive aspect of the incident was that the U.S. Coast Guard was sure to have the way cleared for the actual shipment of the flight hardware. An assist tug also met the ET tug to help control and navigate the channels in the narrow confines of the upper Chesapeake and Curtis Bay.

Curtis Bay. The Army Reserve (USAR) waterfront area at the Defense Logistics Agency (DLA) Depot at Curtis Bay, Maryland was the closest and most convenient harbor area to GSFC. Code 234 interfaced with both the DLA and USAR to use their facilities. Unfortunately, the pier area at the bay was too old and weak to risk the weight of the container/transporter. Code 234 improvised by removing a section of the waterfront fencing and clearing an area of solid ground next to a sea wall to which the ET barge could tie up.

Convoy from GSFC to Curtis Bay. Twenty-four hours prior to the scheduled departure, a last minute route survey was conducted to assure there were no new unknown hazards to the convoy. With only inches to spare in clearing some of the overpasses, a last minute road resurfacing raising the road level could have been disastrous. The survey vehicle, with its measuring pole, would act as the scout vehicle of the convoy leading it safely under the overpasses. On the evening before scheduled departure, the commercial tractors were inspected by Code 230 and hooked up to the transporters. The commercial and government escorts, support equipment truck, and porject vehicles formed up to await the arrival of the Maryland State Police escorts and the midnight departure time. At a little after midnight, the thirteen vehicle parade with amber hazard lights flashing departed for the 30 mile carefully routed trip to Curtis Bay - the beginning of the trip into space.

Convoy Arrival at Curtis Bay & Barge Departure. The convoy arrived at Curtis Bay a little after the scheduled time of 0300, and the transporters were positiioned in the loading area for loading on the ET barge. The ET barge, having arrived the night before, was in position and ready to load. The loading of the transporters was accomplished as scheduled, the HST project passengers accompanying the shipment settled on board, and the barge crew cast off just after first light as planned, and headed out to the bay to begin the ocean journey to KSC. This time, as expected, the Coast Guard assured the way was clear with no obstacles.

Arrival at Cape Canaveral. The ET barge arrived at Port Canaveral where the ocean-going deep water tug was replaced by a river pilot and two shallow water tugs that were capable of navigating the shallow waters of the Banana River to the ET dock at KSC. Code 234 coordinated with KSC logistics personnel to assure the appropriate support vehicles and equipment was on hand to accomplish the off loading. The transporters were delivered to the appropriate processing facilities for their final preparation and integration and test before launch.

The Mission

The success of the HST First Servicing Mission made history and was witnessed by millions around the world. Every newspaper reported, in great detail, the servicing activities of the astronauts of the STS-61 Space Shuttle Endeavour. All major "space logistics" objectives were accomplished; optics were installed that corrected the mirror's blurred images, ORU's were installed to enhance the HST's reliability, and the feasibility and concepts of on-orbit servicing and repair in space were demonstrated and proven. And on earth, logisticians got the space flight hardware and the flight and ground support equipment to the launch pad - and then back home again.

Post Mission Return of Mission Hardware to GSFC

The logistics plan for the return of the hardware from KSC to GSFC was essentially the reverse of that for the trip to KSC, but, there were a few additional challenges. Original planning envisioned the return of the hardware to occur in the spring when the weather along the Atlantic Coast is more conducive to ocean travel. However, after the mission, the HST Project made the decision, based on cost and project requirements, to return the hardware to GSFC before the end of January 1994. The logisticians of Code 230 scurried about to make it happen. Their coordination efforts were hampered by the Christmas holidays that fell between the time that the Endeavour and HST landed and the date the HST was requied at GSFC. A large number of government and contractor personnel involved and knowledgeable with the pre-launch shipment were on well deserved leave, basking in the success of the mission and enjoying the holidays. Many a phone call was answered with "sorry, they are on leave until the middle of January". Nonetheless, this "back-up" team coordinated and executed the effort to bring the hardware "back-up" to GSFC. Once again, the use of the ET barge was coordinated and scheduled to coincide with the delivery of an ET from Michaud to KSC. Everything went according to the plan except that which was beyond anyone's control, the weather. The barge was loaded to capacity with the HST container/transporters, support equipment, an ACTS container destined for GSFC, and an ET cradle to be returned to Michaud. It departed the ET dock at KSC on schedule only to be delayed for a day at Port Canaveral by high seas and swells outside the port. After the barge left the port, the trip north was hampered by more of the bad weather for which the Atlantic winters are famous. After travelling north for a day, no headway was made because high winds out of the north forced the barge to retrace its tracks. Off Cape Hatteras, swells over 20 feet high buffeted the barge and cargo and caused discomfort to the passengers and crew, causing complexions to become pale and green. Meanwhile, the GSFC Washington DC/Baltimore area was experiencing one of its worst winters in decades - ice, sleet, snow, freezing temperatures. When the barge finally reached the mouth of the Chesapeake Bay, the water was calm - calmed by a covering of as much as 4 inches of ice. The ice further slowed the progress of the barge. In the Curtis Bay where the channels are narrow, the water calm, the ice thickest, and the barge would be traveling its slowest, Code 230 called on the U.S. Coast Guard to break ice to enable the tugs to maneuver the barge to the dock more easily. Once at Curtis Bay, the awaiting escort vehicles, tractors, and support vehicles formed up with the transporters for their after-midnight convoy to GSFC and the final leg of the journey.

Summary

The on-orbit servicing of HST was a memorable logistics feat. Getting the hardware to the orbiting HST was a logistics feat in itself. The logistics journey of the HST hardware was over land, over water, and through air & space by truck, by barge, and by shuttle launch vehicle. The "earthy" logistics effort to support the HST First Servicing Mission involved the coordination and cooperation of government and contractor personnel from almost all the NASA Centers, HQ, GSFC, KSC & CCAFS, MSFC, LaRC; the GSFC Project Offices, HST/Code 442, Logistics Management Division/Code 230; the U.S. Army, U.S. Coast Guard, Defense Logistics Agency, and U.S. Air Force. The Hubble Space Telescope Logistics Team, proud of their contributions to the success of the HST First Servicing Mission, is looking forward to and have begun planning the logistics support for the HST Second Servicing Mission scheduled for early 1997.

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Biographies

Dick Kubicko, CPL, is a senior member of SOLE and has over 25 years experience in logistically supporting NASA and USAF space systems. He is an Integrated Logistics Support (ILS) Engineer for the logistics support contractor to the Logistics Management Division/Code 230, at Goddard Space Flight Center (GSFC), Greenbelt, Maryland. Over the last 5 years, Dick has planned, executed, and provided logistics support for most of GSFC's major space flight projects, including HST. He has a B.S. degree in Engineering and a M.S. in Logistics.

Bob Herrick has over 25 years experience in transportation and traffic management in both the commercial and government sectors. Bob has been with NASA in the Logistics Management Division, Transportation and ILS Branch, Code 234, Goddard Space Flight Center, Greenbelt, Maryland for the last seven years. As the Transportation Management Specialist for GSFC, Bob has provided transportation and traffic management support to all GSFC space flight projects, including HST.

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LAUNCH SITE COMPUTER SIMULATION AND ITS APPLICATION TO PROCESSES

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ABSTRACT

This paper provides an overview of computer simulation, the Lockheed developed STS Processing Model, and the application of computer simulation to a wide range of processes. The STS Processing Model is an icon driven model that uses commercial off the shelf software and a Macintosh personal computer. While it usually takes one year to process and launch 8 space shuttles, with the STS Processing Model this process is computer simulated in about 5 minutes. Facilities, orbiters, or ground support equipment can be added or deleted and the impact on launch rate, facility utilization, or other factors measured as desired.

This same computer simulation technology can be used to simulate manufacturing, engineering, commercial, or business processes. The technology does not require an "army" of software engineers to develop and operate, but instead can be used by the layman with only a minimal amount of training. Instead of making changes to a process and realizing the results after the fact, with computer simulation, changes can be made and processes perfected before they are implemented.

COMPUTER SIMULATION OVERVIEW

Computer simulation has traditionally been offered in two very different types of formats. Language-based simulation packages, such as SLAM and SIMAN, require the use of specialized software languages and experts in simulation and coding in order to operate. The simulations performed by these language-based software packages tend to be very general in nature. On the other hand, data-driven simulators use pre-built graphical blocks to simulate common processes found in areas such as manufacturing. While effective for the domain for which they were intended, the pre-built graphical blocks are inflexible and cannot be used to simulate other processes.

With the advent of the Macintosh computer, and now Windows, and with the greatly increased power and affordability of these platforms, a third type of simulation software package has been developed. The hybrid simulation software package combines the power of the language-based packages with the ease of use of the graphical packages. The result is an easy to use, powerful, and flexible simulation package that can be used by the beginner, but also provides the means to develop customized blocks in order to produce very complex and intricate simulations by the experienced modeler.

STS PROCESSING MODEL

The processing of the Space Shuttle at Kennedy Space Center is performed mainly in three types of facilities. The Orbiter Processing Facility (OPF) is used to de-service and remove payload-unique equipment from the orbiter after a mission, perform repairs and modifications, and install equipment and supplies in preparation for the next mission. The Vehicle Assembly Building (VAB) is where the huge external tank (ET) is attached to the solid rocket boosters after they are stacked and is also where the orbiter is attached to the ET. The launch pad is used to prepare the vehicle for launch, including payload installation, fueling, and final checkout. Each of these facilities are limited in numbers; there are three OPF bays, two VAB bays, and two launch pads. The purpose of developing a STS Processing Model is to determine the impact upon the launch rate and facility utilization of events such as changes in the number of orbiters to process, facility shutdown, major flight part unavailability, or GSE disruptions. Other changes, such as the processing impact of a new launch vehicle upon the facilities and the ability of the launch site to effectively process both vehicles can also be modeled. Figure 1 presents an overview of the current STS processing requirements.

The STS Processing Model was developed through the use of the simulation software *Extend + Manufacturing*™ available from Imagine That, Inc., San Jose, Ca. *Extend* is hybrid, library based, iconic-block (graphical element) commercial-off-the-shelf (COTS) simulation software package. The Model describes the behavior of vehicles moving through the major processing facilities, to launch, mission and landing, and then back for processing. The Model operates in a discrete event mode, where events are orbiter movements or other status changes. Event times are driven by orbiter pro-

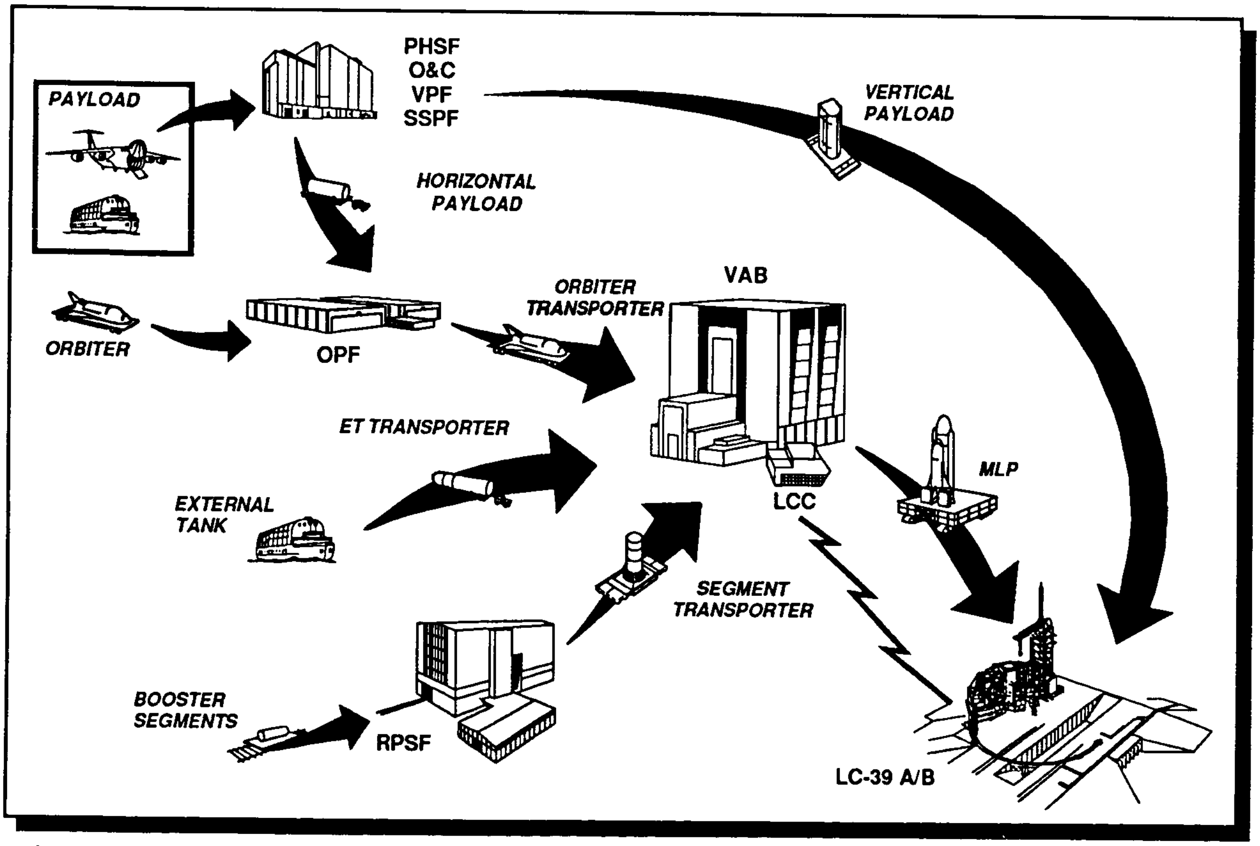

Figure 1. STS Processing Flow

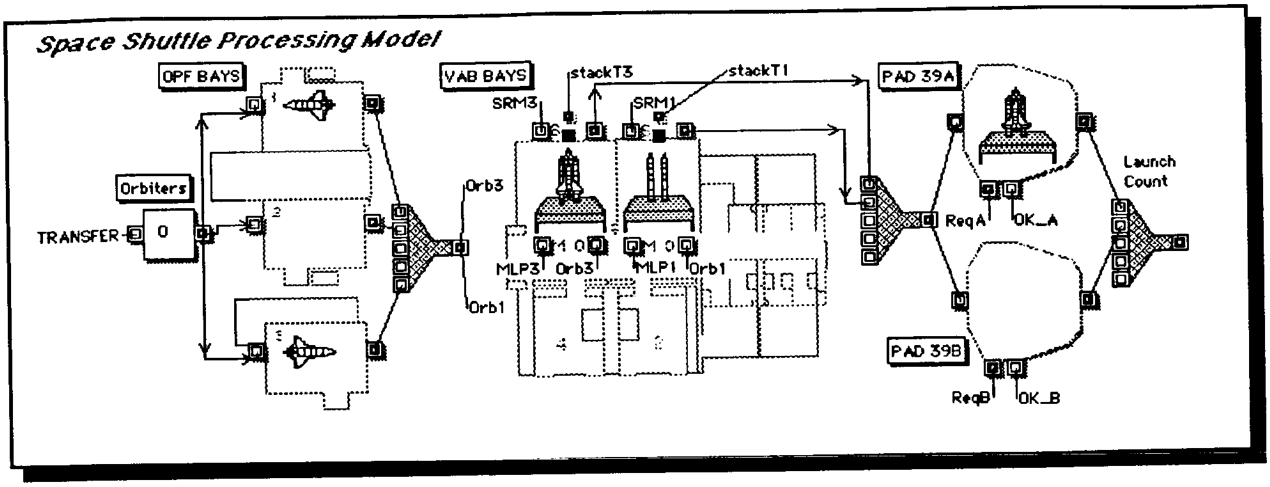

Figure 2. STS Processing Model-Overview

cess durations and the resolution of resource conflicts. An orbiter's process duration is selected from a statistical distribution of achieved processing durations or a default constant. As can be seen in Figure 2, the simulation model of the launch site is very intuitive as the OPF, VAB, and launch pad footprints are used as part of the Model. The process flow on the screen is the same as the orbiter movement toward the launch pad. Additionally, icons of the shuttle, solid rocket boosters, and external tank provide visual clues as to the status of the integrated flow.

Through the use of an input screen, called the Notebook, assets such as orbiters or mobile launcher platforms (MLPs) can be added or deleted in order to perform a "what-if" analysis. These type of changes take about 10 seconds to make, and it takes about 5 minutes to model a years worth of processing to determine the effects on the launch site. Processing times that the Model pulls from the statistical database, such as for the OPF, VAB, or pads, are also shown in the notebook input screen (Figure 3) as the model is running.

The output of the Model is shown in Figure 4. The output, which is a continuation of the Notebook, shows the achieved launch rate, yearly launch rate, facility utilization for each of the

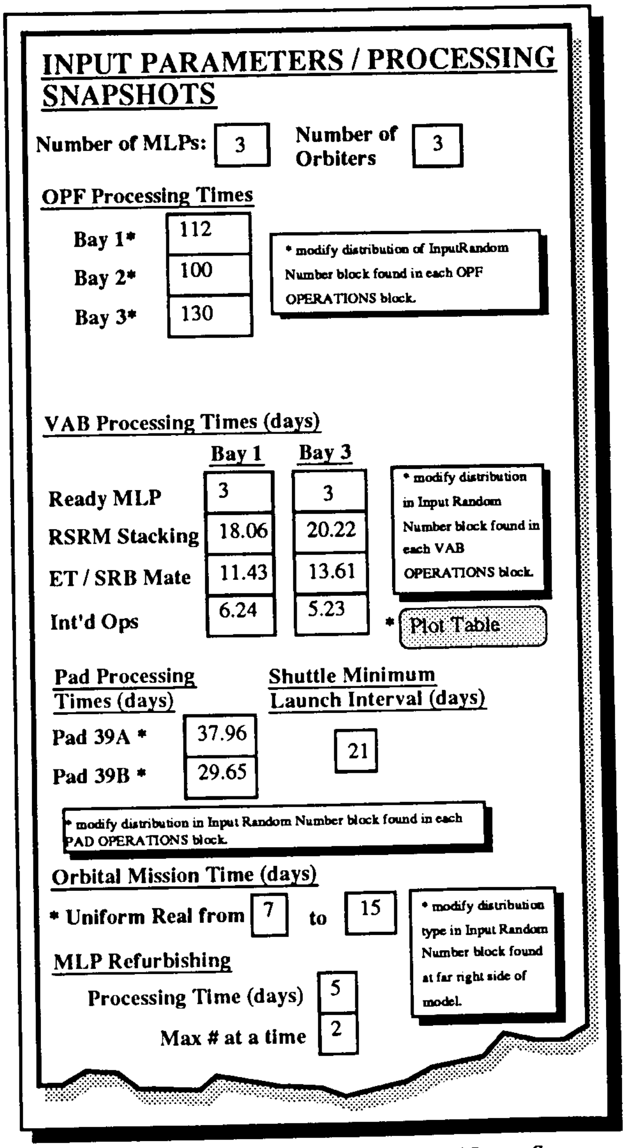

Figure 3. STS Processing Model NotebookInput Screen

facility processing bays and launch pads, and MLP and orbiter availability. A spreadsheet within the Notebook also captures the as-run data for each processing flow so that comparisons and statistical analyses can be made to determine the results of each "what-if" run. Additional data elements can be added to the Notebook as desired.

Each of the facilities represented consist of a hierarchical block. A hierarchical block is composed of a series of logic blocks that represent the logic and events that occur within the facility. For instance, as shown in Figure 5, the processing flow within the VAB consists of a series of library blocks that detail the logic of activities that occur in the VAB. The stacking of the solid rocket boosters, mating of the external tank, and the integration of the shuttle with the stack are represented by a series of logic blocks. The statistics used to represent the durations of each event are taken directly from the actual times achieved from each of the processing flows since 51-L, with the exception of the first flows for Back to Flight and unique flows due to hydrogen leaks.

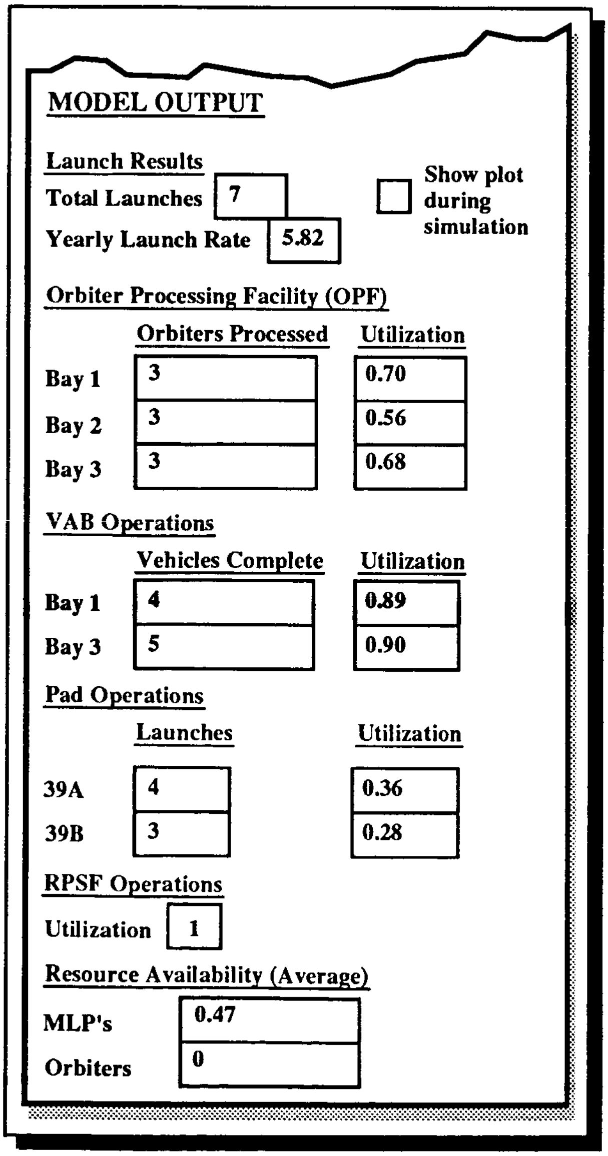

Figure 4. STS Processing Model Notebook Output

Through the use of hierarchical blocks, it is very easy to add or delete facilities to determine the effect on the processing flow, launch rate, or facility utilization. After a hierarchical block is created, it can be added to a library, such as the STS Processing Library, and used to add the facility in the processing flow as desired. It is also easy to delete a facility, simply by selecting and deleting it, to determine the subsequent effect on the processing flow. Either change, whether adding or deleting a facility, takes less than 15 seconds to implement.

Another type of "what-if" analysis that can be done is to determine the effects upon facility utilization and launch rate if an OPF bay is shutdown for one year in order to perform extended duration modifications on an orbiter. As each of the bays and orbiters are the same as far as the model is concerned, OPF bay 3 is selected to have a one year period of downtime. The downtime is selected at a time when the orbiter is in the bay, in order to capture the orbiter for the downtime. A scheduled downtime block is added to the facility block in the OPF hierarchical block and a downtime of one year is selected. After running the Model, it is determined that the launch rate decreases from 7 to 6 while the facility utilization of the remaining OPF facilities increases. A synopsis of the changes incurred due to the addition of one year of OPF

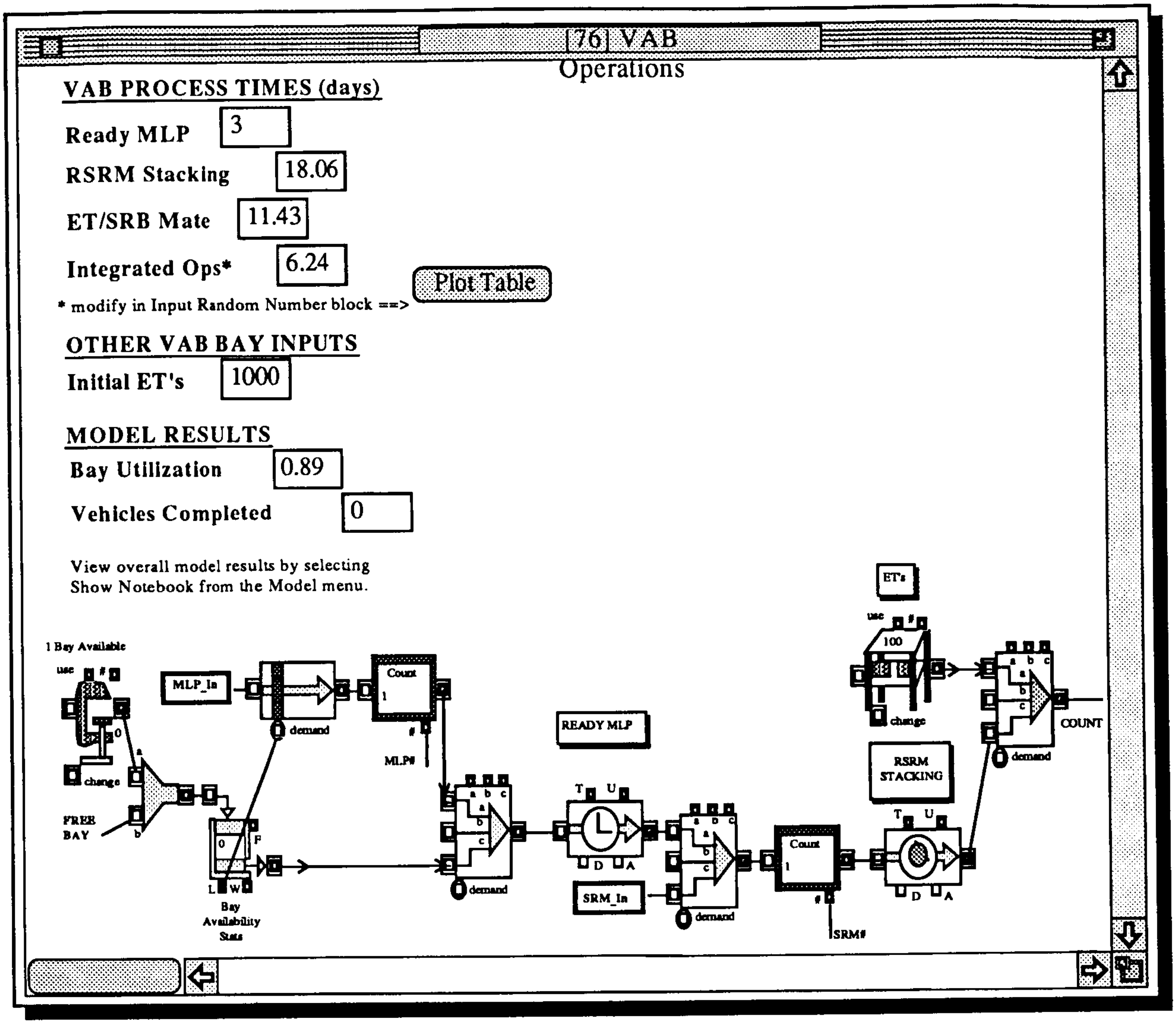

Figure 5. VAB Hierarchical Block

downtime is shown in Figure 6.

Due to its nature as a hybrid simulation package/language, *Extend* enables people with a wide range of ability to change the Model at many levels of detail. The user can double-click on block icons and change dialog parameters. From libraries supplied, the user can get new blocks, connect them, and enter parameters. For more flexibility, the user can enter formulae or equations directly into an Equation block (Figure 7). The simpler groundrules are represented in Equation blocks, so the user can change these or add new blocks to modify groundrules. For the most flexibility, the user can create new primitive blocks by using *Extend*'s built-in C compiler and dialog/icon editors to either modify a pre-existing block or build one from scratch. Most blocks needed are already pre-built. In fact, all but one of the blocks used to build the Model are pre-built.

MODELING PROCESSES

The simulation software and techniques used to develop the STS Processing Model can also be applied to a wide range of processes, such as manufacturing, engineering, and business process reengineering. Specific models may in-

Measurement	Normal Operations	With Downtime
Number of Launches	7	6
OPF Bay 1 Utilization	86.6%	93.9%
OPF Bay 2 Utilization	66.0%	74.1%
OPF Bay 3 Utilization	85.9%	0%
Number of Orbiters on Pad (Ready for launch)	2	0

Figure 6. Effect of OPF Bay 3 Downtime for One Year on the Launch Rate and OPF Utilization

clude logistics inventory analyses, electronic circuit development, or paperwork flow improvement. The software is designed to be used by the layman, and therefore does not require the services of software or modeling experts in order to use.

By modeling processes, a manager shifts the focus from dealing with outcomes to managing the means for achieving customer and business value. Aspects a manager often deals with, such as excess inventory, overtime, expediting, safety problems, worker morale, or delivery performance, are often the cause of the nature of the overall system. However, when identifying a

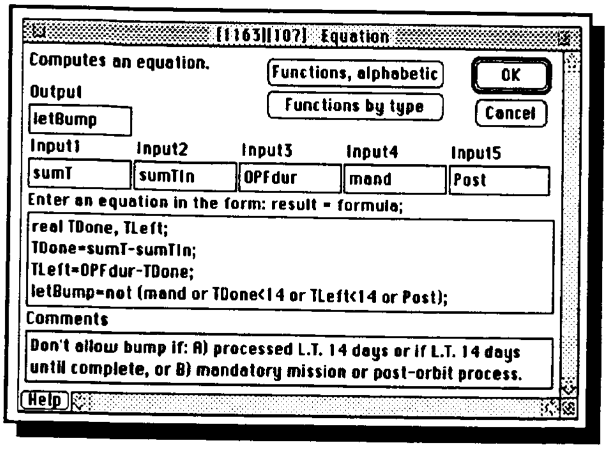

Figure 7. Equation Block Dialog

specific item to change in the system, it is difficult to perceive the overall effect due to the synergy which occurs when all relationships act together. Flow charts can help identify the system parts and process sequence, and spreadsheets can help calculate some mathematical relationships, but the overall cause-and-effect relationships are hard to capture with such tools. A simulation model effectively mimics the dynamic behavior of a flow system, where real-world elements interact when specific events occur, and where behavior may be driven by probabilistic processes and feedback.

Another benefit of simulation is the ability to build or change a process on a computer before it is actually implemented. The building of a simulation model requires that a consensus be developed among the interested parties on what is actually required, which often changes and aligns the perceptions of the parties involved. Based upon up-front understanding of the process and mutually agreed to changes, this "consensual reality" often leads to an improved process when implemented.

CONCLUSION

With the introduction of ever more powerful personal computers and easy to use simulation software such as *Extend*, computer simulation is a now a readily available tool. The STS Processing Model is an example of a fast and flexible tool for the evaluation of shuttle processing scenarios by personnel not familiar with simulation modeling or techniques. In addition, simulation can be used on a wide range of processes to model new developments or changes to existing systems to determine the effectiveness of the processes before they are implemented.

APPLICATION OF DIFFERENT STATISTICAL TECHNIQUES IN INTEGRATED LOGISTICS SUPPORT OF THE INTERNATIONAL SPACE STATION ALPHA

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Abstract

The process to predict the values of the maintenance time dependent variable parameters such as MTBF over time must be one that will not in turn introduce uncontrolled deviation in the results of the ILS analysis such as Life Cycle Cost, spares calculation, etc. A minor deviation in the values of the maintenance time dependent variable parameters such as MTBF over time will have a significant impact on the logistics resources demands, International Space Station Availability and maintenance support costs. It is the objective of this report to identify the magnitude of the expected enhancement in the accuracy of the results for the International Space Station Reliability and Maintainability data packages by providing examples. These examples partially portray the necessary information by evaluating the impact of the said enhancements on the Life Cycle Cost and the Availability of the International Space Station. The examples are as follows:

(1) The Non Electronic reliability data hand book (NPRD) usage by the program

RAM data packages (i.e. a vague approximation of parts count) vs. the actual stress method of prediction;

(2) Constant failure rate prediction vs. what distribution it should be;

(3) Percentage of the parts on the International Space Station with constant failure rates in relation to the overall International Space Station configuration;

(4) Miscellaneous enhancements that can benefit the overall program RAM data packages.

1. REFERENCES

A. CSA SOW dated December 1993;

B. Space Station Freedom External Maintenance Task Team, July 1990, final report;

C. External Maintenance Solution Team, January 1991, final report.

D. SPAR-SS-SASD-0265, Back up

drive unit MTBF prediction, March 03 1993;

E. SPAR-SS-R-0482, Limited Life Items List for MSS, May 1993;

F. SPAR-SS-SASD-0260, Joint backup relay unitpreliminary MTBF prediction, March 03 1993;

G. SPAR-SS-SASD-0259, LEE backup relay unit preliminary MTBF prediction, March 03 1993;

H. SPAR-SS-SASD-0115, Joint electronic unit MTBF prediction, Oct 27 1993;

I. SPAR-SS-R-0613, Orbit replaceable unit (ORU) list for MSS, May 1993;

J. Applications of Space Logistics Engineering in Quantitative Risks assessment and management of Space Station Freedom, AIAA 1991, Cocoa Beach, Florida, F. Sepehry-Fard.

K. Reliability worksheet on the SSRMS joints, dated May, 28, 1993.

2. OBJECTIVE

2.1 The objective of this report is to note the factors (environmental, pre-operational, others) which must be taken into account during the process of accurately predicting the maintenance time dependent variables in a space environment; to indicate the potential delta if the real failure rate parameters are not used for such models as life cycle costs and availability; and to recommend actions to enhance the program RAM packages by achieving a more thorough accounting for all anticipated factors.

3. INTRODUCTION

3.1 In response to Reference A task, a series of three (3) reports which describes the initial approach to conduct refinement processes for the maintenance time dependent parameters such as MTBF in order to accurately forecast the Logistics Support requirements shall be submitted. This is the third report of the three reports. The paramount and complex problem relative to the time dependent maintenance variable parameters became apparent as a result of the investigations performed on the program's RAM packages. Find attached as Annex A, a description of the cost delta between the Weibull and exponential failure density distribution on the SSRMS joint.

3.2 This report includes examples to indicate the potential delta if the real failure rate parameters are not used in subsequent resource modelling activities. These examples partially portray the necessary information by evaluating the impact of the said deficiencies on the Life Cycle Cost and the Availability of the MSS. The examples are as follows:

3.2.1 The Non Electronic reliability data hand book (NPRD) usage by the RAM data packages (i.e. a vague approximation of parts count) vs. the actual stress method of prediction;

3.2.2 Constant failure rate prediction vs what distribution it should be;

3.2.3 Percentage of the parts on the MSS with constant failure rate in relation to the overall MSS configuration;

3.2.4 Miscellaneous deviations inherent in the RAM data packages.

3.3 The NPRD reliability assessment of the ORUs vs. actual stress method prediction

3.3.1 Ref. E states that the failure rates were obtained using the NPRD. Let us examine this way of assessment and evaluate the impact on the logistics support requirements. Examination of reliability worksheets performed by Ref. K dated 28, May 1993, elucidates explicitly that all the joints are treated the same generic way. In other words, all the joints are assumed to have the same MTBF figure and the assessment of the failure rate utilizes the NPRD-91. In view of the fact that different joints on the MSS go through different stress levels and furthermore there is not any layout and/or schematics in the NPRD-91 in order to justify this analysis and similiarization. This universal treatment of the joints can be extremely off with respect to the prediction of the time dependent maintenance parameters such as MTBF, MDT, etc which directly affect and are the key drivers for the accurate forecast of operational and steady state availability, spares and support equipment requirements. The following examples illustrate these deviations.

3.4 Percentages of Electronic/Electrical, Electromechanical, Mechanical, Structural Mechanical and Structural parts on the MSS.

3.4.1 The following illustrate the percentages of Electronic/ Electrical, Electromechanical, Mechanical, Structural Mechanical and Structural parts on the MSS. According to Ref. I and B, there are 83 and 213 CSA ORUs, respectively. Our analysis utilizes the number provided in Ref. I and categorizes the ORUs in 5 different classes. This analysis is based on engineering judgement and approximation on the percentages of the parts count embodied in each ORU. This assessment assumes that the failure and repair distributions allocated for different family of products (i.e. Electrical, Mechanical, etc.) will not be changed as a result of exposures to Solar Flares, Atomic Oxygen, Micrometeorite, etc.

The different family of products percentages on the MSS are as follows:

27% of failures related to Electromechanical parts, 19% of failures related to mechanical parts, 3% of failures related to Structural mechanical parts, 27% of failures related to Structural parts belong to other distributions than exponential such as Normal, Lognormal, Gamma, Weibull, etc. which should be assessed according to the methodologies explained in this report.

3.4.2 Report 2 states that exponential failure distribution to predict MTBF is almost exclusively used for electronic equipment. Exponential failure distribution describes the situation wherein the hazard rate is constant which can be shown to be generated by a Poisson process. Some particular applications of this model include:

A. Items whose failure rates do not change significantly with age;

B. Complex and repairable equipment without excessive amounts of redundancy;

C. Equipment for which the early failures or "infant mortalities" have been eliminated by "burning in" the equipment for some reasonable time period.

3.4.3 Only about 24% (i.e. Electronic/Electrical family of products on the MSS) of these assessments belong to exponential failure distribution. Depending on the value of β, the weibull distribution function can take the form of the following distributions as follows:

$\beta < 1$	Gamma
$\beta = 1$	Exponential
$\beta = 2$	Lognormal
$\beta = 3.5$ Normal	(approximately)

Thus, it may be used to help identify other distributions from the life test data or other data from the previous spacecraft anomalies (backed up by goodness of fit tests, see recommendation) as well as being a distribution in its own right. In order to determine the distribution densities for the different family of products, we have to look at the reliability and life tests data backed up by other actual data which best represent the real life scenario of the products in question. These assignments of failure density distributions can, as recommendation suggests, be verified and validated by means of goodness of fitness tests.

3.5 The following calculation demonstrates the potential delta in what is being proposed vs what it should be as far the cost of the impact on the Life Cycle Cost and Availability of the MSS are concerned. The assumptions for calculating these figures and the subsequent items A - F are provided accordingly:

A. It is intended to benefit the MSS program by $5 Billion over 30 years (Ref. J);

B. Initial Acquisition cost[1] 1.2 Billion

C. CSA's predicted MTBF[2] 242,752 Hours

D. Recalculated MTBF using NPRD3 329.47 Hours

E. Total down time[4] 25 Hours

F. Total corrective maintenance time[5] 5 Hours

1 See Ref. J.

2 See Ref. K.

3 This calculation utilizes NPRD-91. NPRD uses a constant failure rate model for generic failure rate predictions. This calculation does not in any way represent the real case scenario rather it is intended to show the possible swing in NPRD values using different justifications and approximations (MSS Reliability Worksheets, Ref. K, uses the Ground fixed as the environment. Based on the same kind of justifications and approximations, utilization of Ground Mobile environment can also be substantiated). Please also see Annex A.

4 MTTR = 5 hours (Ref. J), Assume overhead of 500% therefore:

Total Down Time 5 Hours x 5 = 25 Hours

5 MTTR of Joint Drive Module = 5 Hours (Ref. J)

Total Corrective Maintenance Time = 5 Hours

3.5.1 It is quite clear, from the above, that the steady state Availability will be affected as a result of tremendous inaccuracy inherent in the method of calculation and the results of the CSA's time dependent maintenance parameter prediction such as MTBF, MDT, etc.

$$A(t) = A_s = \frac{MTBF}{MTBF + MTTR}$$

A. It is evident from the above, that uncontrolled deviation in the MTBF and MDT values would mean totally inaccurate results for the Availability. This means that effective planning related to the assembly, operation and utilization of the SSRMS, MSS and/or the International Space Station can not be performed;

B. Furthermore, the opportunity costs, needless delay in schedule, costs due to unavailability or surplus of the support equipment, as result of the above, are expected;

C. As an example, the cost of launch per lbs is $5000. Each joint is 252 lbs and the price of each joint is more than $4 Million. The inaccuracy of the time dependent maintenance parameters (i.e. MTBF, MDT, etc.) values means inability to accurately predict the occurrence of the failures (random and wear out) as a function of time. This means that adequate logistics resources may not be available at the right time. This furthermore means that there may be an operational impact due to insufficient support resources.

3 6 The Miscellaneous deviations inherent in the RAM data packages include but are not limited to the following:

3.6.1 Ref. H, in section 4.0, refers to microcircuit failure rates based on junction temperatures of 55 C. Examination of the parts breakdown of the same document in its IC section clearly indicates that a good portion of the IC s used are CMOS. CMOS technology utilizes the channel not junction. Junction terminology is merely used for bipolar products which are, in view of their high power consumption vs the CMOS, not looked at very favourably. Furthermore, it is understood that the Russians are capable of repair and removal of their ORUs at the component level, and that the ISSA program may be pursuing methods of increasing in-situ maintenance and intermediate maintenance on-orbit. It is therefore necessary for us to understand the physics of the components used on the MSS to preclude unnecessary delay and support costs from an effective logistics support requirements program plan for the MSS.

3.6.2 Examination of Ref. F. elucidates explicitly that the MTBF obtained, based on parts count prediction, for the Joint Backup Relay Unit (LBRU) is 37,907,506 hours this translates to over 4000 years. It has been the author's experience, during the FMECA on the SARSAT, that based on some failure modes (such as shorting the DC capacitors) the following failures may occur on the MSS:

a. Drainage of the solar power system without the ability to detect the failure mentioned above (the redundant fuses rating, if any, may be between the threshold value and its blowing value based on this failure mode) and/or;

b. Relay contacts sticking due to continuous over current flow.

3.6.3 Examination of Ref. E. shows that the criteria for life Limiting Items are based on linear relationships (i.e. Table 2-1-1-1, 13 years mentioned for SSRMS joints based on initial 3.5 years of Space Station operation). As it has clearly been stated in report 1, 2 and backed up an by example in this report, this assumption and/or observation is not valid. Each of the ORUs and their subsystems should be assigned a failure and repair density function. The predictions for LLI (Life Limited Items) should only then performed from the above-mentioned distributions.

4. RECOMMENDATION

In view of the aforementioned deviations, it is highly recommended that the following tasks be performed:

4.1 Case studies in relation to the different failure and repair distribution density functions in order to determine, quantify and timeline the Logistics Support and spares requirements for the MSS, etc;

4.2 Verification and validation on the maintenance time dependent parameters such as MTBF and MDT using statistical tests such as D test, chi square test, goodness of fitness tests in order to validate and verify the distributions assigned to different family of products, etc;

4.3 The following areas need also be addressed in order to incur an accurate logistics support requirements:

a. Common mode failures;
b. Common cause failures;
c. Maintenance/Operations induced failures;
d. Life limited items;
e. Duty cycle (i.e. duty cycle does not necessarily increase failure rates)
f. Construction induced failures;
g. Advances in technology;
h. Mid Life Update (MLU) of the MSS.

4.4 MSS and SSRMS Probability of survival, operational and steady state availability assessment based on different mission criticality scenarios;

4.5 Research in frequency of occurrence of cosmic rays, Micrometeorite, flares, atomic oxygen, magnetic storms, etc. in order to quantify and substantiate their impact on the Life Cycle cost and Logistics support requirements of the MSS;

4.6 Determination of time truncated and failure truncated events for planning the required logistics resources;

4.7 Determination and level of space insurance based on quantitative risks assessment and management of the MSS and SSRMS;

4.8 Research in order to determine the effects of the combined environments, i.e. cosmic rays and micrometeorite, in order to accurately determine and quantify the Logistics Support and spares requirements, etc;

4.9 Spacecraft anomalies data base set up in order to exploit the space industry failure and repair historical data (i.e. MIR) to be able to baseline the time dependentmaintenanceparameters accordingly;

4.10 In order to accurately forecast the resource demands as a function of time during the operation phase, it is vital to accurately assess the following with the amalgamation of the space stringent requirements such as flares, cosmic rays, micrometeorite, etc. These amalgamation should quantify the impact of the said parameters, either by themselves or combined, on the following areas of investigations:

A. FMECA;
B. Parts Application Review;
C. Single Point failures
D. Life Limited Items List;
E. Safety and Hazard analysis; and
F. Reliability Predictions.

These assessments are in part due to the possible marriage overtones among the different ORU functionalities, etc.

ANNEX A: The cost delta between the weibull and exponential failure density distribution on the SSRMS joint

1. The usefulness of the models based on constant failure rates is limited because they do not adequately account for the fact most mechanical products have a failure rate which is not constant with time as shown in figure 1.

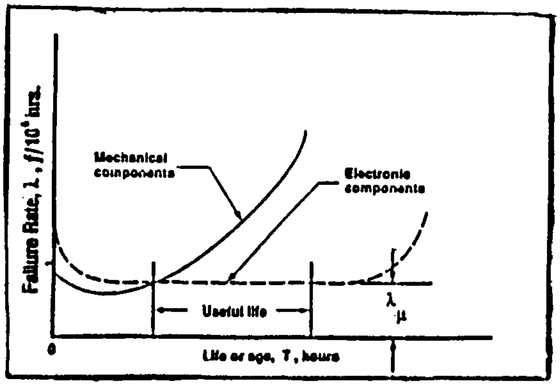

Figure 1: Typical Hazard plots for Electronic and Mechanical components

The problem that we face in trying to use the exponential (i.e. Mil-HDBK-217, etc.) prediction model for mechanical components is that there is no "useful life" period in which the failure rate is approximately constant with time. We have a situation as shown in figure 2. The constant failure rate only corresponds to the actual failure rate at a specific time which is unknown.

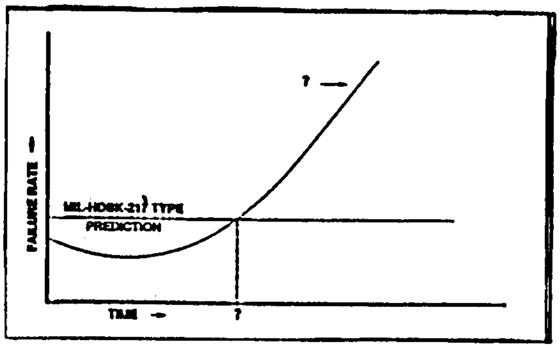

Figure 2: Comparison of Prediction and Actual Failure Rate.

By using the Weibull distribution to represent the

RAM data for the mechanical parts such as the joints on the SSRMS, the non constant failure rate can be dealt with. The equations for the reliability function and failure rate function for the Weibull distribution are shown in report 2. The Reliability (t = n) = e^{-1} = 0.368, the failed population = 63.2% and λ (t = n) = β/n. It can be seen from the last equation that at a time equal to the Weibull characteristics life, the failure rate function simplifies to being equal to the Weibull slope divided by the characteristics life. If we modify the "MIL-HDBK-217 Type" prediction model to predict the failure rate at a time equal to the Weibull characteristics Life we have the condition shown in figure 3. This modification can be accomplished by adjusting the base failure rate in order to obtain agreement between the proposed prediction model and the more accurate model based on Weibull failure density function. In order to accomplish this modification, it is necessary to accurately determine the Weibull probability parameters from different sources of data (i.e. reliability and space qualification testing, field experience, etc). By plotting the failures based on Weibull failure density distribution on a Weibull probability paper, we should see the indication of a convex shape which is very likely due to the effect of infant mortality failures. The shape of the these kinds of plot suggests that it could reasonably be fitted by the mixture of two distributions. The RMAT default value for the β is 5. Based on the current situation, we assign two sets of β values namely 3 and 5. We will evaluate the delta of what is being proposed based on constant failure rates and its impact on the overall logistics support cost for the joints of the SSRMS. The following assumption have been made:

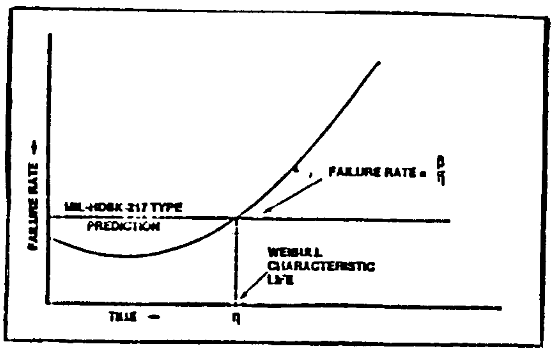

Figure 3: Prediction Equals Actual Failure Rate At Weibull Characteristics Life

a. SPAR MTBF for the joint is accurate and is 242,752 hours;

b. All the parts in the joint resemble a Weibull failure density distribution (i.e. even though there are some electrical/electronic components on the joint, they are also assumed to follow a Weibull failure density functions). In real life, it is customary to categorize the different family of products according to their respective failure and repair density functions and obtain the cumulative probability of survival and failure in order to come up with much more accurate results);

c. For Weibull distribution:

λ (t=n) = β/n
λ = 3/242,752

<u>λ = 12.35 failures E-6 Hours</u>

or:
for β = 5

λ = 5/242752

<u>λ = 20.6 failures E -6 Hours</u>

For exponential distribution:

<u>λ = 4.2 failures E -6 Hours</u>

d. The delta (ratio) for the two Weibull failure density distribution cases (i.e. β = 3 and β = 5) and the exponential failure density distribution with constant failure rate are 290% and 490%, respectively.

e. The following table illustrates the unnecessary cost due to these types of inaccurate maintenance time dependent parameters prediction:

λ(SPAR)	λ (β=3)	λ (β=5)	RATIO (β=3/e)	RATIO (β=5/e)	Ps	P_f
4.12 F/10E6HRS	12.35 F/10E6HRS	20.6 F/10E6HRS	290%	490%	36.8%	63.2%

* These values represent the best case scenario. In other words, they only represent the delta between the assessment of constant failure rate vs. non constant failure density distribution (i.e. the Weibull distribution). In reality, if we were to include all the other RAM data deviations (i.e. Orbital debris, Cosmic Rays, etc.), the level of the ineffectiveness of the current Logistics Support Requirements would have been much more pronounced.

INTEGRATED LOGISTICS SUPPORT ANALYSIS OF THE INTERNATIONAL SPACE STATION ALPHA, BACKGROUND AND SUMMARY OF MATHEMATICAL MODELLING & FAILURE DENSITY DISTRIBUTIONS PERTAINING TO MAINTENANCE TIME DEPENDENT PARAMETERS

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Abstract

The process to predict the values of the maintenance time dependent variable parameters such as MTBF over time must be one that will not in turn introduce uncontrolled deviation in the results of the ILS analysis such as Life Cycle Cost, spares calculation, etc. A minor deviation in the values of the maintenance time dependent variable parameters such as MTBF over time will have a significant impact on the logistics resources demands, International Space Station Availability and maintenance support costs. There are two types of parameters in the logistics and maintenance world:

a. Fixed;
b. Variable

Fixed parameters, such as cost per man hour, is relatively easy to predict and forecast. These parameters normally follow a linear path and they do not change randomly. As an example, if the cost per man hour in 1993 is $76, this rate will amount to $78.28 per hour for 1994 considering the inflation rate of 3% per annum. However, the variable parameters subject to the study in this report such as
MTBF do not follow a linear path and they normally fall within the distribution curves which are discussed in this publication. The very challenging task then becomes the utilization of statistical techniques, as illustrated in this report, to be able to accurately forecast the future non linear time dependent variable arisings and events with a high confidence level. This, in turn, shall translate in tremendous cost savings and improved availability all around.

1. REFERENCES

A. Space Station Freedom External Maintenance Task Team, July 1990, final report;

B. External Maintenance Solution Team, January 1991, final report.

2. INTRODUCTION

2.1 A series of three (3) reports which describes the initial approach to conduct refinement processes for the maintenance time dependent parameters such as MTBF in order to accurately forecast the Logistics Support requirements were completed. This is the second of the three reports. The paramount and complex problem relative to the time dependent maintenance variable parameters became apparent as a result of the investigations on the programs's RAM packages.

2.2 The process to predict the values of the maintenance time dependent variable parameters such as MTBF over time,as report 1 (this report is labelled as "INTEGRATED LOGISTICS SUPPORT ANALYSIS OF THE INTERNATIONAL SPACE STATION, AN OVERVIEW OF THE MAINTENANCE TIME DEPENDENT PARAMETER PREDICTION METHODS ENHANCEMENT" and is published in this symposium) and annex A of this report elucidate, can not be treated by the same process as the program's data packages suggest as this will introduce uncontrolled deviation in the results of the ILS analysis such as Life Cycle Cost, spares calculation, etc. Furthermore, the very acute problems ofmicrometeroites, Cosmic rays, flares, atomicoxygen, ionization effects, orbital plumes and all the other factors that differentiate maintainable space operations from non maintainable space operations and/or ground operations must be accounted for by the program's RAM data packages. Therefore, these parameters need be subjected to a special and complex process.

2.3 FSF, per the direction of CSA management, elected to investigate these parameters due to the complexity of the process involved and because these parameters' values and data packages have shown not to have a common denominator as far as the method of assessment and calculation are concerned; a minor deviation in their values will have a significant impact on the logistics resources demands, MSS availability and maintenance support costs.

2.4 There are two types of parameters in the logistics and maintenance world:

A. Fixed;
B. Variable

2.5 Fixed parameters, such as cost per man hour, is relatively easy to predict and forecast. These parameters normally follow a linear path and they do not change randomly. As an example, if the cost per man hour in 1993 is $76, this rate will amount to $78.28 per hour considering the inflation rate of 3% per annum. However, the variable parameters subject to the study in this report such as MTBF do not follow a linear path that they normally fall within the distribution curves discussed in annex A.

2.6 The very challenging task then becomes the utilization of statistical techniques, as illustrated in this report, to be able to accurately forecast the future non linear time dependent variable arisings and events with a high confidence level. This, in turn, shall translate in tremendous cost savings and improved availability all around.

2.7 The objectives of this report are two fold:

A. To explain the requirements for accurate prediction of different structural, mechanical and electrical ORU's time dependent maintenance parameters such as MTBF; and

B. Describe, in general terms, the steps required (including a mathematical background) to predict the MTBF values over time in order to increase accuracy of the results pertaining to the MSS spares modelling & calculation, availability, Life Cycle Cost, etc.

3. <u>REQUIREMENTS FOR PREDICTING MTBF VALUE AS FUNCTION OF TIME</u>

3.1 The random predicted value and the actual value fluctuations for time dependent maintenance parameters such as mean time between failures (MTBF) and mean down time (MDT) which are the key drivers for effective logistics support planning, proved to be stumbling blocks in providing the accurate and necessary logistics support requirements. This deficiency is due to the fact (Ref. annex A) that structural, mechanical and electrical family of products belong to different distribution functions. There is at present no single method available to accurately predict these future arisings and their frequency and effectively estimate logistics support requirements for the MSS.

3.2 The necessary mathematical background that the reader has to become familiar with is provided in annex A.

3.3 Figure 3.3.1 shows the flow diagram explaining the top level steps necessary to refine the time dependent maintenance parameters such as MTBF.

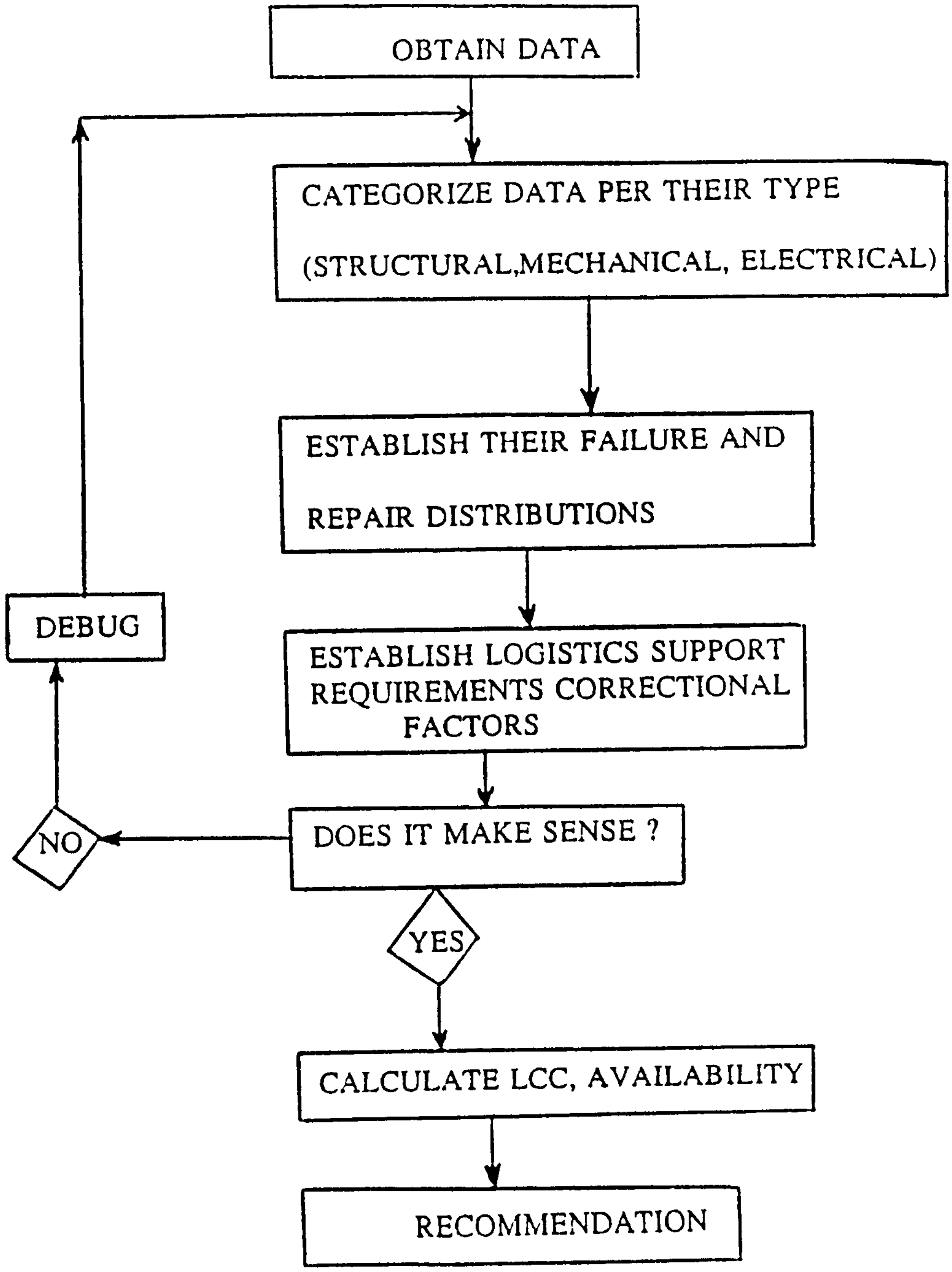


FIGURE 3.3.1 REFINEMENT PROCESS FOR THE TIME DEPENDENT MAINTENANCE PARAMETERS

ANNEX A

STATISTICAL DISTRIBUTION TYPES

1. There are many standard statistical distributions which may be used to model the various maintenance time dependent variable parameters such as MTBF (Mean Time Between Failures) and MDT (Mean Down Time). The particular distribution used depends upon the nature of the data, in each case. Following is a short summary of some of the distributions most commonly used in statistical analysis and the criteria for their use. The distributions can be categorized in two criteria:

A. Continuous distributions; and

B. Discrete distributions.

CONTINUOUS DISTRIBUTIONS

1.1 Continuous distributions, as the name implies, are distributions with continuous shape and form. They primarily consist of the following distributions:

Normal distribution

1.1.1 There are two principal applications of the normal distribution to statistical analysis. One application deals with the analysis of items which exhibit failure due to wear, such as mechanical devices. Frequently the wear out failure distribution is sufficiently close to normal and that the use of this distribution for predicting or assessing maintenance time dependent variable parameters, after preliminary assessments, can be shown to be valid.

1.1.2 The other application deals with the analysis of manufactured items and their ability to meet specifications. No two parts made to the same specification are exactly alike. The variability of parts leads to a variability in systems composed of those parts. The design must take this part variability into account, otherwise the system may not meet the specifications requirement due to the combined effect of part variability. Another aspect of this application is in quality control procedures. The basis for the use of normal distribution in this application is the central limit theorem which states that the sum of a large number of identically distributed random variables, each with finite mean and variance, is normally distributed. Thus, the variations in value of electronic component parts, for example, due to manufacturing are considered normally distributed.

1.1.3 The failure density function for the normal distribution is

$$f(t) = \frac{1}{\sigma(2\pi)^{\frac{1}{2}}} \exp\left[-\frac{1}{2}\left(\frac{t-u}{\sigma}\right)^2\right]$$

Where:

U = The population mean

σ = The population standard deviation, which is the √ of the variance.

Lognormal distribution

1.1.4 The lognormal distribution is the distribution of a random variable whose natural logarithm is distributed normally; in other words, it is the normal distribution with ln t as the variable. The density function is:

$$f(t) = \frac{1}{\sigma t (2\pi)^{\frac{1}{2}}} \exp\left[-\frac{1}{2}\left(\frac{\ln t - u}{\sigma}\right)^2\right]$$

for $t \geq 0$

Where the mean = $\exp\left(u + \frac{\sigma^2}{2}\right)$

the standard deviation = $\left[\exp(2u + 2\sigma^2) - \exp(2u + \sigma^2)\right]^{\frac{1}{2}}$

and where u and σ are the mean and the standard deviation of ln t.

1.1.5 The lognormal distribution is used in statistical analysis of semiconductors and fatigue life of certain types of mechanical components. Its main application is really in maintainability analysis of time to repair data.

Exponential distribution

1.1.6 This is probably one of the most important distributions in statistical analysis and is almost exclusively for statistical analysis of electronic equipment. It describes the situation wherein the hazard rate is constant which can be shown to be generated by a Poisson process. This distribution is valuable if properly used. It has the advantages of:

A. Single, easily estimated parameter (λ);
B. Mathematically very tractable;
C. fairly wide applicability;
D. is additive - that is, the sum of a number of independent; exponentially distributed variables is exponentially distributed.

1.1.7 Some particular application of this model include:

A. Items whose failure rates do not change significantly with age;
B. Complex and repairable equipment without excessive amounts of redundancy;
C. Equipment for which the early failures or "infant mortalities" have been eliminated by "burning in" the equipment for some reasonable time period.

1.1.8 The failure density function is

$$f(t) = \lambda e^{-\lambda t}$$

for t>0, where λ is the hazard (failure) rate and the reliability function is:

$$R(t) = e^{-\lambda t}$$

the mean life $(\theta)= 1/\lambda$, and, for repairable equipment, the MTBF = $(\theta) = 1/\lambda$.

Gamma distribution

1.1.9 The gamma distribution is used in statistical analysis for cases where partial failures can exist, i.e., when a given number of partial failures must occur before an item fails (e.g, redundant systems) or the time to second failure when the time to failure is exponentially distributed. The failure density function is:

$$f(t) = \frac{\lambda}{\Gamma(\alpha)} (\lambda t)^{\alpha-1} e^{-\lambda t}$$

$$for\ t > 0$$

$$where\ u = \frac{\alpha}{\lambda}$$

$$SD = \frac{\alpha^{\frac{1}{2}}}{\lambda}$$

Where λ is the failure rate (complete failure) and α the number of partial failures for complete failure or events to generate a failure. $\Gamma(\alpha)$ is the gamma function

$$\Gamma(\alpha) = \int_0^\infty x^{\alpha-1} e^{-x} dx .$$

which can be evaluated by means of standard tables. Where $(\alpha-1)$ is a positive integer, $\Gamma(\alpha)=(\alpha-1)!$, which is usually the case for most statistical analysis, e.g, partial failure situation. For this case the failure density function is:

$$f(t) = \frac{\lambda}{(\alpha-1)!} (\lambda t)^{\alpha-1} e^{-\lambda t}$$

which, for the case of $\alpha=1$ becomes the exponential density function, previously described. The gamma distribution can also be used to describe an increasing or decreasing hazard (failure) rate. When $\alpha>1$, h(t) increases; when $\alpha<1$, h(t) decreases.

Weibull distribution

1.1.10 The Weibull distribution is particularly useful in statistical analysis since it is a general distribution which by adjustment of the distribution parameters, can be made to model a wide range of life distribution characteristics of different classes of engineered items. One of the versions of the failure density function is:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right]$$

Where: β is the shape parameter n is the scale parameter or characteristic life (life at which 63.2% of the population will have failed)γ is the minimum life

1.1.11 In most practical statistical analysis situations, γ is often zero (failure assumed to start at t = 0) and the failure density function becomes

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

and the reliability and hazard functions become

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

$$h(t) = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1}$$

DISCRETE DISTRIBUTIONS

1.2 Discrete distributions, as the name implies, are distributions with non-continuous shape and form. They primarily consist of the following distributions:

Binomial distribution

1.2.1 The Binomial distribution is used for those situations in which there are only two outcomes, such as success or failure, and the probability remains the same for all trials. It is very useful in statistical analysis and quality assurance work. The probability density function (PDF) of the binomial distribution is:

$$f(x) = \binom{n}{x} p^{x} q^{(n-x)}$$

$$\text{where } \binom{n}{x} = \frac{n!}{(n-x)!x!}$$

$$\text{and } q = 1 - p$$

f(x) is the probability of obtaining exactly x good items and (n-x) bad items in a sample of n items where p is the probability of obtaining a good item (success) and q (or 1-p) is the probability of obtaining a bad item (failure).

1.2.2 The cumulative distribution function (CDF), i.e., the probability of obtaining r or fewer successes in n trials, is given by

$$F(x;r) = \sum_{x=0}^{r} \binom{n}{x} p^{x} q^{(n-x)}$$

POISSON DISTRIBUTION

1.2.3 This distribution is used quite frequently in statistical analysis. It can be considered an extension of the binomial distribution when $n \geq 20$ and $p \leq 0.05$.

If events are Poisson distributed, they occur at a constant average rate and the number of events occurring in any time interval are independent of the number of events occurring in any other time interval. For example, the number of failures in a given time would be given by:

$$f(x) = \frac{a^{x}e^{-a}}{x!}$$

where x is the number of failures and a is the expected number of a failures. For the purpose of statistical analysis, this becomes:

$$f(x;\ \lambda,\ t) = \frac{(\lambda t)^{x}e^{-\lambda t}}{x!}$$

Where:

λ = failure rate
t = length of time being considered
x = number of failures

The reliability function, R(t), or the probability of zero failures in time t is given by:

$$R(t) = \frac{(\lambda t)^{0}e^{-\lambda t}}{0!} = e^{-\lambda t}$$

or our old friend the exponential distribution.

1.2.4 In the case of redundant equipments, the R(t) might be desired in terms of the probability of r or fewer failures in time t. For that case:

$$R(t) = \sum_{x=0}^{r} \frac{(\lambda t)^{x}e^{-\lambda t}}{x!}$$

1.2.5 Figure 1.1 illustrate the density function, reliability function and hazard rate for the normal, Exponential, Gamma, Weibull and Lognormal distributions.

1.2.6 Figure 1.2 shows the shapes of failure density and reliability functions of commonly used discrete distributions.

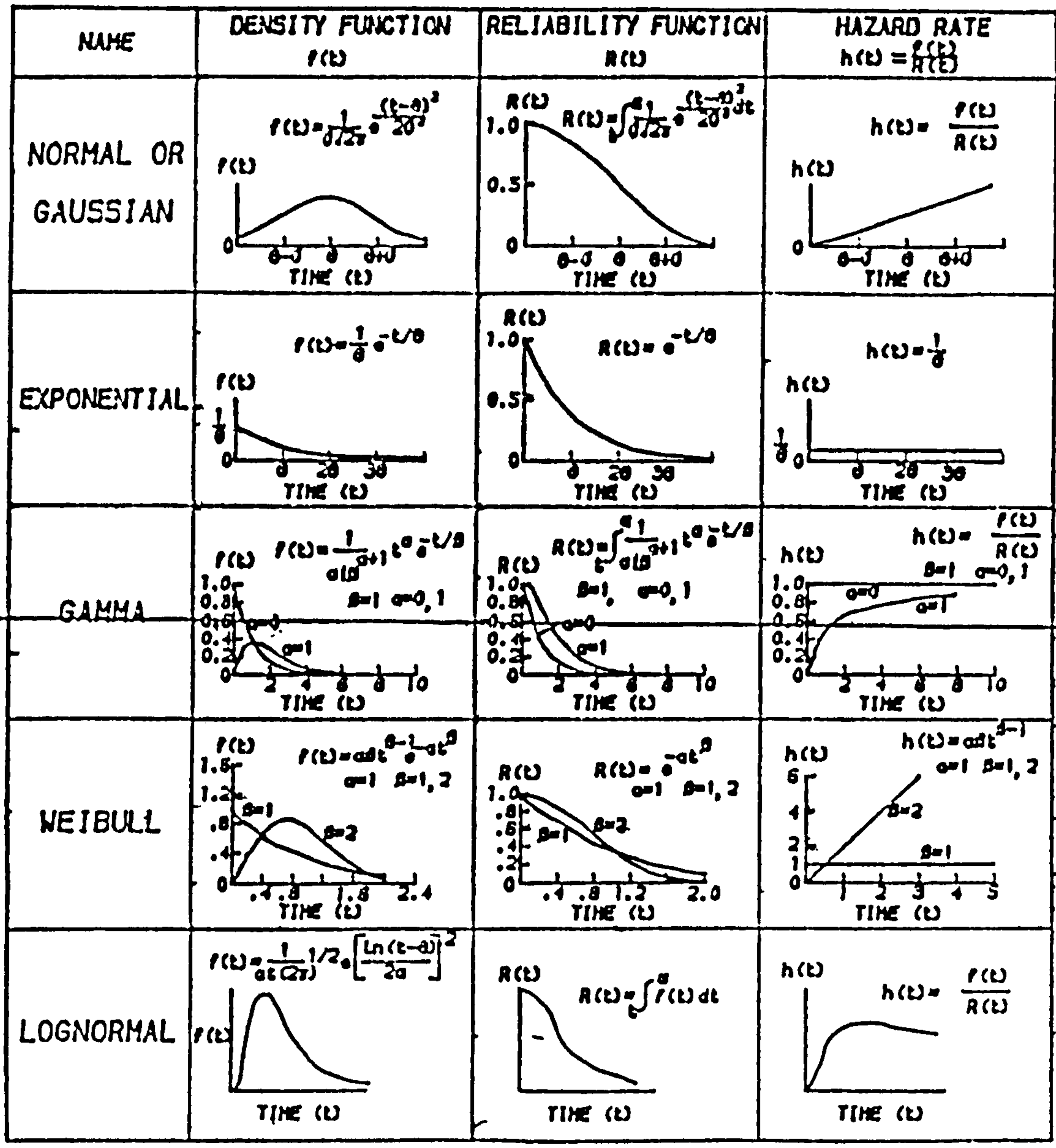


FIGURE 1.1 DENSITY FUNCTION AND HAZARD RATE FOR NORMAL EXPONENTIAL, GAMMA, WEIBULL AND LOGNORMAL DISTRIBUTIONS

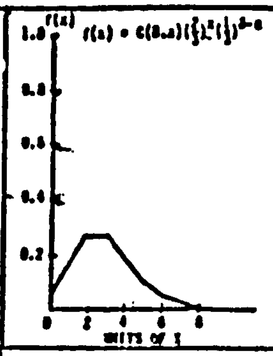
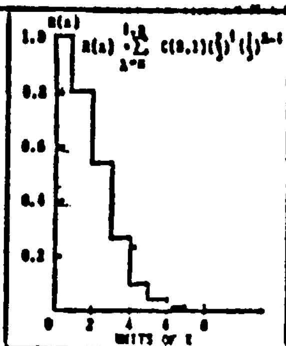
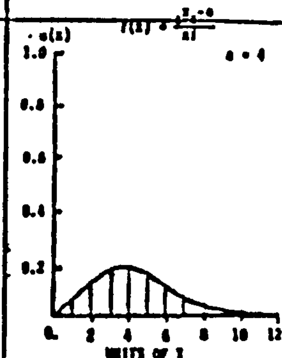
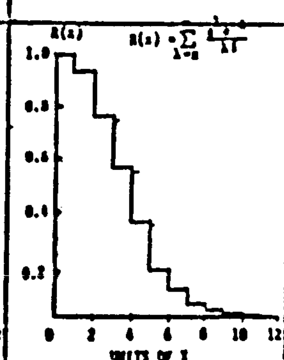
TYPE OF DISTRIBUTION	PARAMETERS	PROBABILITY DENSITY FUNCTION $f(x)$	RELIABILITY FUNCTION $R(x)$
BINOMIAL	MEAN, $\mu = np$ Std. deviation, $\sigma = \sqrt{npq}$ $\binom{n}{x} = \frac{n!}{(n-x)!x!}$		
		$f(x) = \binom{n}{x} p^x q^{n-x}$ $\left\{ \begin{matrix} n = 8 \\ p = 2/3 \end{matrix} \right\}$	$R(x) = \sum_{i=x}^{n} \binom{n}{i} p^i q^{n-i}$ $\left\{ \begin{matrix} n = 8 \\ p = 2/3 \end{matrix} \right\}$
Poisson	Mean, $\mu = a$, $= \lambda t$ Std. deviation, $\sigma = \sqrt{a} = \sqrt{\lambda t}$		
		$f(x) = \frac{a^x e^{-a}}{x!}$ $= \frac{(\lambda t)^x e^{-\lambda t}}{x!}$ $a = \lambda t = 4$	$R(x) = \sum_{i=x}^{\infty} \frac{a^i e^{-a}}{i!}$ $= \sum_{i=x}^{\infty} \frac{(\lambda t)^x e^{-\lambda t}}{x!}$ $a = \lambda t = 4$

FIGURE 1.2 SHAPES OF FAILURE DENSITY AND RELIABILITY FUNCTIONS OF COMMONLY DISCRETE DISTRIBUTIONS

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A PROBABILISTIC TOOL THAT AIDS LOGISTICS ENGINEERS IN THE ESTABLISHMENT OF HIGH CONFIDENCE REPAIR NEED-DATES AT THE NASA SHUTTLE LOGISTICS DEPOT

035803

8P.

By J. V. Bullington*, J. C. Winkler*, D. G. Linton PhD.†, S. Khajenoori PhD.‡

Abstract

The NASA Shuttle Logistics Depot (NSLD) is tasked with the responsibility for repair and manufacture of Line Replaceable Unit (LRU) hardware and components to support the Space Shuttle Orbiter. Due to shrinking budgets, cost effective repair of LRUs becomes a primary objective. To achieve this objective, it is imperative that resources can be assigned to those LRUs which have the greatest expectation of being needed as a spare. Forecasting the times at which spares are needed requires consideration of many significant factors including, for example, failure rate, flight rate, spares availability, and desired level of support, among others. This paper summarizes the results of the research and development work that has been accomplished in producing an automated tool that assists in the assignment of effective repair start-times for LRUs at the NSLD. This system, called the Repair Start-time Assignment System (RSAS), uses probabilistic modeling technology to calculate a need date for a repair that considers the current repair pipeline status, as well as, serviceable spares and projections of future demands. The output from the system is a date for beginning the repair that has significantly greater confidence (in the sense that a desired probability of support is ensured) than times produced using other techniques. Since an important output of RSAS is the longest repair turn-around time that will ensure a desired probability of support, RSAS has the potential for being applied to operations at any repair depot where spares are on-hand and repair start-times are of interest. In addition, RSAS incorporates tenants of Just-In-Time (JIT) techniques in the connotation that the latest repair start-time (i.e., the latest time at which repair resources must be committed) may be calculated for every failed unit. This could aid in reducing the spares inventory for certain items, without significantly increasing the risk of unsatisfied demand.

Introduction

The problem addressed by this research project was to produce a tool that could aid in reducing logistics operations costs while maintaining timely hardware availability to the Orbiter program, as well as, future space programs. Increasingly tight budget restrictions are continually putting greater pressure on the entire space program to reduce operations costs -- or price itself out of business. Reductions in labor-intensive processes, coupled with novel approaches for providing the spare and repair aspects of logistics, are desperately needed. The broad objective of this project was to develop an advanced technology application that is capable of reducing labor intensity and production time for selected tasks currently performed in the logistics process.

The research team investigated several possible areas within current Orbiter Logistics operations for application of advanced technology before finally deciding to focus on a new repair review board task. This area satisfied the criteria we felt necessary for a successful project of this nature. Those criteria were as follows:

1. Experts performing the specific task must be available in-house, and willing to cooperate with the project.
2. The potential for cost savings as compared to similar analyses performed manually must be clearly evident.

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3. The required input data must be accessible to the research team.

The intent of the repair review board was that a group of management level personnel from several Orbiter hardware support areas would meet at regular intervals throughout the year to assess the criticality of need of various items in for repair at the depot. Those items that have a sufficient level of support remaining for extended periods into the future represent situations where the repair could potentially be deferred indefinitely. This postponement of repair time has the potential for saving money by not expending valuable resources on non-critical items. Due to the complexity of Orbiter systems, the aging of the fleet, and relatively low flight rates corresponding to small sample sizes, a math model alone is recognized as insufficient for adequately determining need. Due to this shortcoming, the specific objective of this research grew into an investigation of the feasibility of combining expert system technology and probabilistic modeling to assist in assigning repair start times at the NASA Shuttle Logistic Depot (NSLD). The initial assessment of the benefits of the technology insertion indicated the potential for: 1) reduced labor intensity in the logistics product support area, 2) more uniform and consistent assignment of repair start times at the NSLD, 3) better planning and management control of capacity at the logistics depot, and 4) possibly assisting in the depot scheduling process.

The concept for the selected system was to combine algorithmic models for computing Supportability Turn Around Time (STAT), discussed later in this paper, and heuristic knowledge of Logistics Engineering Experts into a decision support tool called the Repair Start-time Assignment System (RSAS). As it turns out, the process of selecting candidate repairs for deferral has an analogous, and complimentary process for determining priority of need. Since the logistics engineers at the depot are deeply familiar with the prioritization end of the problem (as opposed to seeking deferrals), and since selecting units with priority leaves a large quantity of items to be deferred by default, it was decided to make use of the available prioritization domain expertise. The tool's refined purpose is to aid logistics engineers at the NSLD in assessing Line Replaceable Unit (LRU) part items for priority of repair need. Those parts that rank low in the resulting priority can then be more intelligently, and safely examined for potential repair deferral.

System Architecture

The following requirements were established for the development of the RSAS system. As an initial approach, the prototype would be concerned with providing analysis for only those LRUs that are reparable at the NSLD. The prototype system was to be a stand-alone environment developed on a DOS/PC running under the MS/Windows 3.x operating system. The system input would be provided through a semi-automated data capture procedure, that could eventually be expanded to full on-line database access. System output would, at a minimum, consist of a probabilistic estimate of the likeliest number of days before the LRU repair operation should start, and a repair start-date that has been determined by backing out the number of days required (on average) to repair units of this type. This probabilistically determined need-date could then be adjusted heuristically by application of rules via an expert system knowledge base if appropriate. Figure 1 represents the architectural view of the RSAS prototype. The RSAS is modularly constructed from three distinct components: 1) Data Capture component, 2) Algorithmic component, and 3) Expert System component. The following sections provide a more detailed discussion of these components.

Data Capture Component

At the start of the project, the data items used by the logistics engineers in their decision making process was located in many different databases and report sources. Examples of some of these were the LE's Desk Report, Generalized System II (GSII) Repair File, Logistics Inventory Management System (LIMS), Material Inventory Control & Information System (MICIS), and many custom reports dynamically pulled down from various mainframe databases as necessary. A set

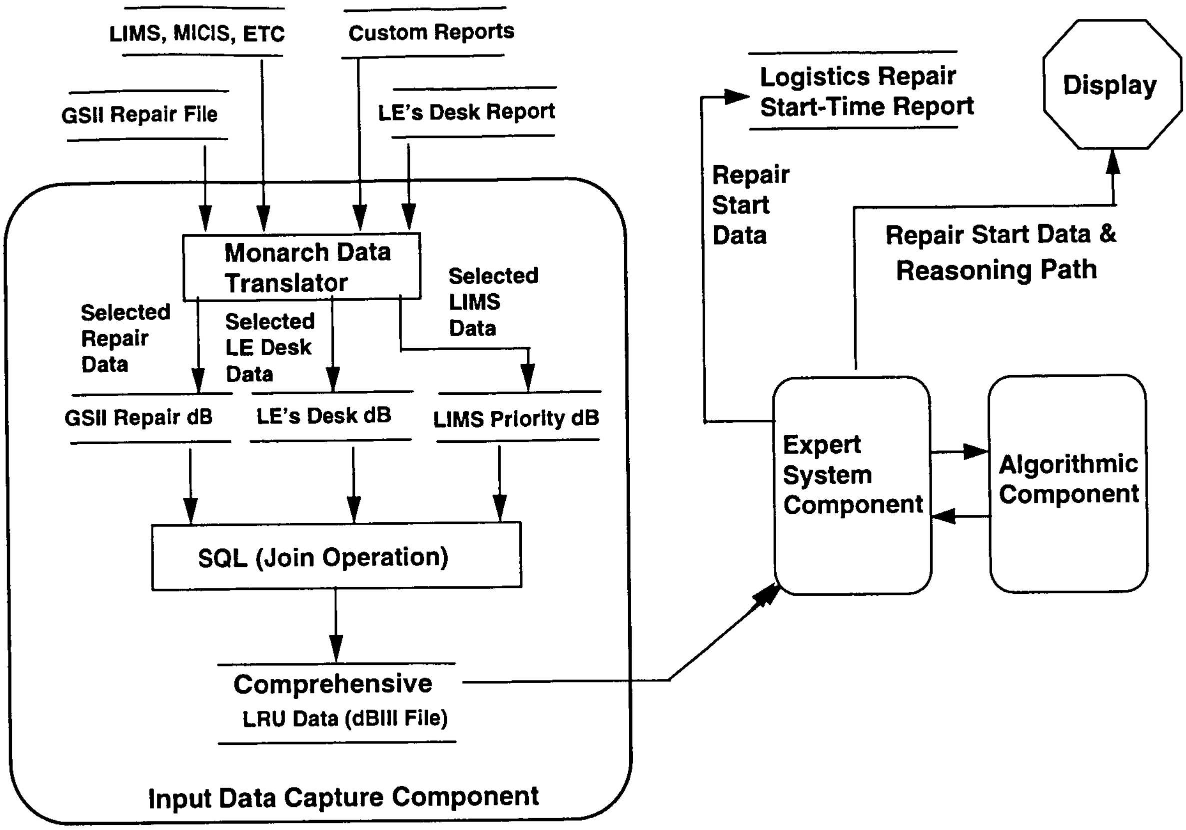

Fig 1. The Prototype Configuration of RSAS

of templates were developed which identified the required data items used for an analysis and the data source. Using the templates, reports containing the data items for a selected group of parts in repair were generated and stored on a floppy diskette. The report files were then converted into individual dBase III files consisting of only the data items of interest from each source using a software application called Monarch Data Translator.

Finally, the separate files were merged through appropriate use of the Structured Query Language (SQL) outer-join operation to form a comprehensive data input file for the RSAS. Space limitations prevent displaying a full row of typical input data elements; however, Table 1 is an example of a partial input file for the prototype RSAS. A complete table could have in excess of one hundred columns for each item in for repair. The information contained in the input file allowed the system to answer questions concerning, for example: Flight Power On Time (FPOT), Ground Power On Time (GPOT), whether the part's use is hourly or flight cycle based (HOUR), the expected Repair Turn Around Time (RTAT), both individual and group Vehicle Maintenance Demand Rate (IND_VMDR and GRP_VMDR), Quantity Per Vehicle for each Orbiter (QPV102, QPV103, QPV104, QPV105), and the serviceable spares available on the shelf (SPARES). There were a number of advantages to the data capture procedure just described. For example, it helped to automate the data capture process by providing a set of templates that identified the source of each required data item. The defined templates resulted in an efficient procedure for capturing decision data for many parts during a single batch run. System validation was also enhanced since, in most cases, we employed the same sources of data as the experts in performing their analysis. Finally, It was easy to modify the templates when new data items were incorporated into the analysis process and hence, maintenance of the data capture component was enhanced. By using a modular system design

Table 1. Example of Partial RSAS Data Input File

FPOT	HOUR	RTAT	GPOT	CON	IND_VMDR	GRP_VMDR	QPV102	QPV103	QPV104	QPV105	SPARES
260	HRS	96.66	60	0.9	0.72	0.72	7	7	7	7	5
260	HRS	96.66	60	0.9	0.72	0.72	7	7	7	7	5
260	HRS	96.66	60	0.9	0.72	0.72	7	7	7	7	5
260	HRS	34.86	60	0.9	0.29	0.29	2	2	2	2	2
8	HRS	113.51	8	0.5	16.75	16.75	3	3	3		5

approach that separates the data capture component from the core processing element of the system, we increased the opportunities for using the RSAS system at various locations throughout the logistics program (e.g., HDA, management, the LE's desktop machine, etc.). This also limited and localized the modifications required to the RSAS in the event that the mainframe LRU data repositories were substantially changed, which, as it turns out, is exactly what began to occur. After testing the system with the LEs for a short time, it was learned that many of the data systems we had been using were to be consolidated onto a local mainframe in Oracle 7 formats. With the modular approach, the data capture component is completely interchangeable. The prototype configuration shown in Figure 1 allowed the use, testing, and verification of RSAS based solely on data obtained from specific data query pulls. By replacing only the semi-automated front end with one capable of Oracle access, a fully automated system for assigning repair start-times to an entire inventory of repair items is possible.

Alternatively, a desktop tool can be implemented where data input is provided interactively by a Logistics Engineer, or a member of management. This provides a what-if type of calculator never before available to the logistics engineering community. Such an implementation is shown in the screen capture image of Figure 2.

The Algorithmic Component

The principal feature of the Repair Start-Time Assignment System (RSAS) is the calculation of STAT values based on a desired level of probability-of-sufficiency (POS). POS is the probability of the event: "a spare is available to replace a failed unit." NASA defines the level of support that must be maintained for Orbiter systems. Thus, if POS = 0.90 = 90%, this means that when a unit fails, the inventory/repair system must be positioned such that 90% of the time a spare is immediately available for replacement. The term STAT is related to POS and indicates the maximum repair turn-around time permitted for a failed part that would still ensure a desired POS- value. In particular, for a failed Line-Replaceable Unit (LRU) not yet under repair at time t, STAT is the longest repair turn-around time from t that would ensure that the probability of no under-support during the interval t to t+STAT is POS (i.e., the probability is POS that a spare will be available for any unit that fails during t to t+STAT).

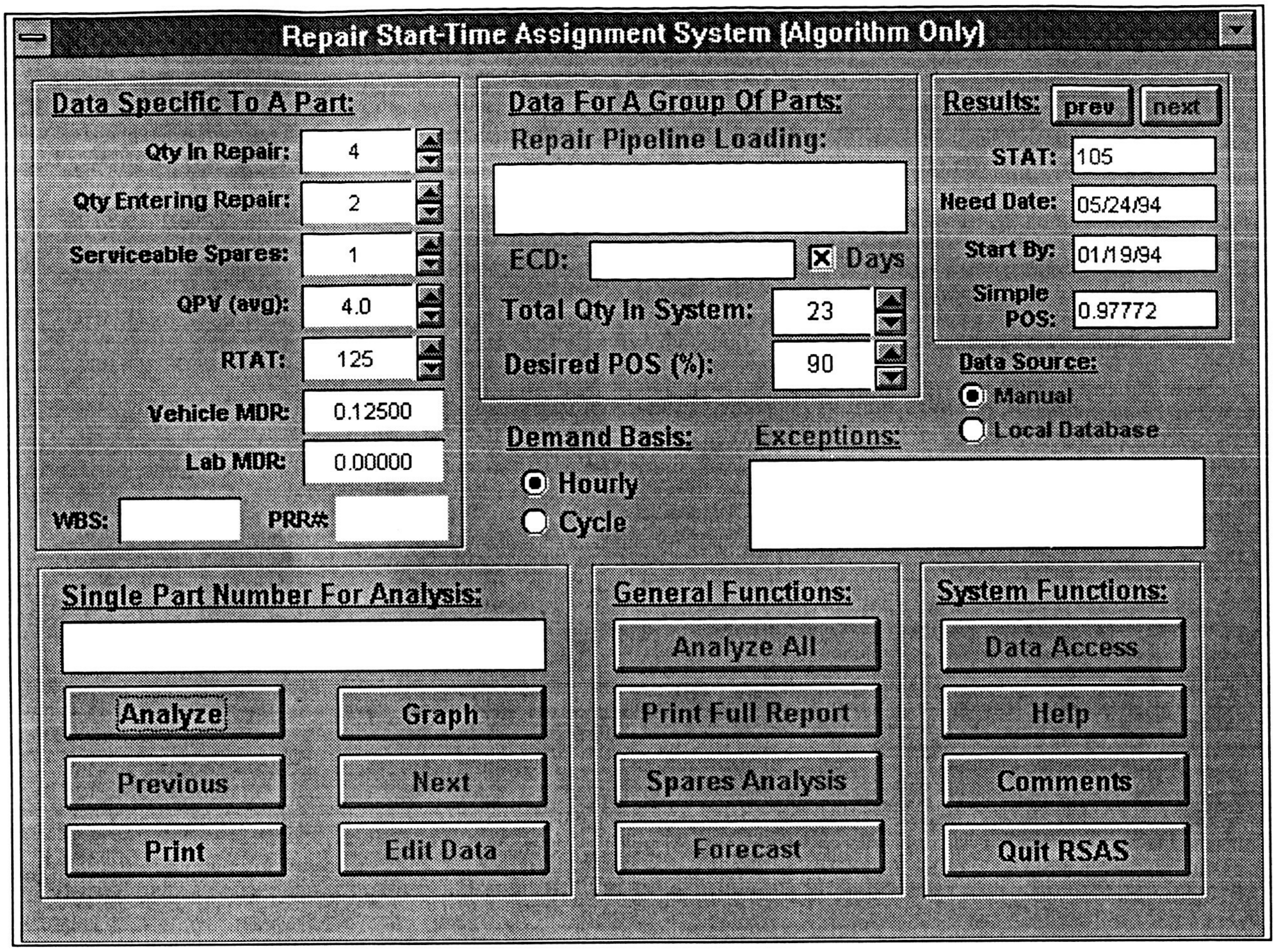

Fig 2. Screen Capture Image of RSAS Implemented as Desktop Tool

In order to calculate STAT values based on a given POS level for an LRU, modifications of equations conceptualized in notes from Dear were employed[1]. The Poisson process, and its associated probability law, is the fundamental building block used to obtain the equations from which STAT-values are found. Currently, the modifications and mathematical proofs of these equations are the subject of ongoing research whose findings and results will be reported in related papers[2]. Briefly, a STAT value is determined mathematically as the root of a particularly configured exponential equation that considers demand rate, available spares, and the quantity and respective completion date of like items in repair. It represents a reasonable starting point in the assignment of repair need-dates that is founded on accepted failure modeling practices[3]. As of this writing, various automated root-finding techniques are under investigation. In any case, once a STAT-value has been found, subtracting the expected repair time (say E{R}) from the computed STAT-value will yield the latest time that repairs on this failed LRU may start. This idea is pictured in Figure 3 following.

The Expert System Component

The expert system component of the RSAS prototype was implemented using the Level5 Object expert system shell[4]. The system knowledge base consisted of a set of rules elicited from the experts. The system level control of program flow for the prototype was also encoded into the rule base. Upon activation, the program evaluated and interpreted the input data file. Using data analysis logic encoded in the knowledge base, the program extracted and

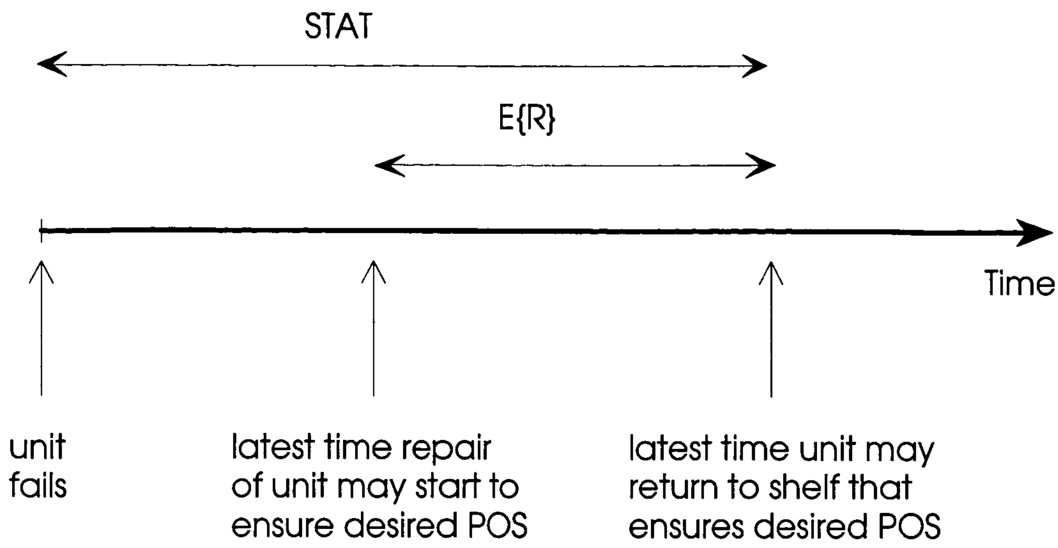

Fig 3. Graphical Representation of Latest Repair Start Time Based on STAT, POS, and Expected LRU Repair Time E{R}

formulated the necessary input for the algorithmic component. It then activated the algorithmic processing which returned a value of STAT for a failed part that would ensure a given value of POS. Various additional pieces of data from the input file were then used by the expert system to adjust the algorithmically calculated STAT values by applying heuristic knowledge in a manner similar to the way the human experts would respond. The expert system component produced two forms of output. The first form was a graphical display utilizing MS-Windows interface controls to present processing results, to list the reasoning path taken in the derivation of those results, and to indicate any special exceptions encountered that would require additional human expertise. Second, the system could produce a hard copy report that presented the results of a complete analysis for a large quantity of repairs. Table 2 provides an example of a partial output file generated by the system. In the table, entries were made for every part number analyzed (PART_NUMBER, PART_NAME), the minimum (DMIN), maximum (DMAX), and best value (STAT) of days before this item is needed (calculated using the algorithm), the expert system adjusted repair start time (ARST), and notification of any rules fired due to unusual circumstances that still require human expert intervention (CONDITION, REASON).

Although the Level5 Object expert system shell proved invaluable for prototype development, it was decided against using it in the final system due to the cost of licensing the distributable product. Instead, an embeddable form of the C Language Integrated Production System (CLIPS) expert system shell was developed[5]. Since CLIPS is a NASA developed package, it has no additional per seat licensing cost. Also, because of its highly procedural nature, the program control portion of the system was removed from the knowledge base and implemented in event driven code associated with the user interface. This greatly simplified the knowledge base, and made the final system tremendously more flexible and maintainable. Finally, since the expert system portion of RSAS is highly dependent on large amounts of data to make viable adjustments to the need-dates, and due to the major platform transition for data sources mentioned previously, it was decided to generate a version of the RSAS without the expert system module. The user interface for this version, shown previously in Figure 2, is currently in use by the LEs as of this writing. It provides for manual data entry only, and relies on the

Table 2. Example of Partial RSAS Output Report

PART_NUMBER	PART_NAME	DMIN	STAT	DMAX	ARST	CONDITION	REASON
MC409-0005-0045	UNIT, HDSET	31	48	69	-48		
MC409-0014-0006	TACAN	8	5	238	-109		
MC409-0015-0006	RADAR ALTIME	3,810	4,098	4,098	4,064		
MC409-0017-0006	DECODER	20	0	325	0	EXCEPTION	Failure Analysis Required

human expert to amend the need-date as necessary. A comment feature has been added so that the LE can annotate his reasoning for making adjustments to algorithmically calculated need-dates. This aids in refinement of the expert system knowledge base.

Significance of Results

- The development of a working RSAS system through the combination of the three modules just discussed is the most significant result of this research. It demonstrates the feasibility of combining expert system technology and probabilistic models to produce repair start times having higher confidences than could be expected from an algorithm alone. This concept has the potential for being merged with a fully integrated repair scheduling system.

- The data capture component is significant in that it is a semi-automated process for obtaining large amounts of decision-specific data from multiple data sources through standard reports. It draws from the most recent sources available to provide high integrity decision data. Due to the modularity of the system, it can be modified or exchanged as required by changing data requirements or improvements in the data repositories.

- The expert system component is significant in that it attempts to make decisions by applying a set of heuristics captured from logistics engineering experts, similar to the way the experts would make decisions. Since the knowledge base contains a set of rules that represent the combined domain expertise of many logistics engineers, the results and decisions of the expert system component can be more uniform and consistent than those produced by the individual human experts. This feature leads to decisions that are inherently more programmatic.

- The algorithmic component is significant in that it calculates STAT values that take into consideration not only the number of spares on the shelf, but also the expected completion of units currently undergoing repair to provide a more accurate projection of the expected time of need for the unit under analysis. The use of this data is recognized as an important feature in the performance of local spares analysis. Also, it has led to an understanding of better ways of displaying data such as POS, repairs in process, and so on, that are more meaningful to the logistics engineers than a purely tabular format.

Conclusions

A prototype system combining expert system technology and probabilistic modeling was developed. This prototype demonstrated the feasibility of producing potential repair start-times for LRUs entering the repair process at the NSLD in an automated fashion. The system was designed with modularity and maintainability as central features. The need-dates produced by the RSAS were immediately recognized by the Logistics Engineers at the NSLD for their accuracy, and the overall system was quickly accepted for use due to its user friendly interface.

The system was easily extended into other types of hardware maintained at the depot, for example, Government Supplied Equipment (GSE). New areas for the system's use continue to be pursued. It is expected that this application will eventually be integrated into a general repair scheduling system.

Acknowledgements

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Reliability Driven Space Logistics Demand Analysis

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209 936

Abstract

Accurate selection of the quantity of logistic support resources has a strong influence on mission success, system availability and the cost of ownership. At the same time the accurate prediction of these resources depends on the accurate prediction of the reliability measures of the items involved. This paper presents the method for the advanced and accurate calculation of the reliability measures of complex space systems which are the basis for the determination of the demands for logistics resources needed during the operational life or mission of space systems. The applicability of the method presented is demonstrated through several illustrative examples.

1. Introduction

Practice shows that, in a majority of cases, the shortage of logistic support resources causes a much higher delay in performing a maintenance task than the delays caused by any other reason [2]. Consequently, the users select, control and manage resources, the quantity of which has a strong influence on system availability and the cost of ownership. An over-estimated quantity of results in a higher support cost with a great deal of capital tied up, whereas an under-estimated quantity results in a reduction of availability/profit. Therefore, the accurate prediction of the quantity and content of logistic support resources required is imperative for cost effective support of the operation and maintenance process. At the same time the accurate prediction of these resources depends on the accurate prediction of the reliability measures of the items involved.

One of the most frequently used reliability measure, in engineering practice, is the hazard function, $z(t)$, defined as:

$$z(t) = \frac{f(t)}{R(t)} \quad (1)$$

where: $f(t)$ is a probability density function of the random variable which represents time to failure, TTF, and $R(t)$ is a corresponding reliability function which quantitatively expresses the probability that the failure will not occur up to time t, $P(TTF > t)$. Generally speaking, the hazard function, could be an increasing, decreasing or constant function of time, which depends on the real process of the change in the physical condition of the item analysed. In the case that the time to failure is modelled by the exponential distribution, the above function becomes:

$$z(t) = \frac{f(t)}{R(t)} = \frac{\lambda exp(-\lambda t)}{exp(-\lambda t)} = \lambda \quad (2)$$

The above expression has a constant value, and it is known as a failure rate. It is necessary to stress that Eq. 2 is applicable only in the cases where the time to failure can be modelled by the exponential probability distribution, which is applicable to a time independent processes.

Analyses of models which deal with the determination of the quantity of the logistic support resources needed [1],[4],[7],[8], shows that all of them are based on the failure rate. However, this assumption is not always correct, because there are many items whose failures are influenced by the time dependent processes, like corrosion, thermal deformation, fatigue, bedding-in, and similar. In these cases the failure rate, which reflects a time independent process has to be replaced with a hazard function which represents a time dependent process. Therefore, the application of models based on the constant failure rate to the determination of number of spares needed and other resources for items whose hazard function is decreasing or increasing during operational life, could generate results far from optimal [5].

Thus, the main aim of this paper is to demonstrate the approach to the reliability modelling of the complex systems which would provide correct results relative to the prediction of the demands for the logistic support resources.

2. Present Practice

In order to set up the scenario for this paper the very simple example related to the evaluation of the mean time to failure of the complex system, $MTTF$s, will be used.

Thus. let as look at a system which consists of three items, say A, B, and C, connected in series from the point of view of reliability. The task is to calculate the $MTTF$s of the system, if the $MTTF_A = MTTF_B = MTTF_C = 1000$ hours.

This very simple problem could be easily solved by applying the following technique which is commonly used by many reliability practitioners. Thus, the failure rate of each module is $\lambda_A = \lambda_B = \lambda_C = 1/1000 = 0.001$, and as the items are connected in series the sum of their failure rates will give the failure rate of the system. Thus, the failure rate of the system is $\lambda_s = 0.003$, which means that the mean time to failure of the system will be $MTTF_s = 333.3$ hours.

Many reliability engineers would finish the analysis at this point and use the obtained value for the $MTTF$s of the system in all further calculations related to the provision of the logistic support resources.

Regarding this paper the above example is only the starting point. First of all, it is necessary to stress that the result obtained is valid only under the assumption of the constant failure rate. In cases where the items considered demonstrate increasing or decreasing failure rates during operational life this approach would provide an incorrect solution.

In order to illustrate the point made above, let us use the same example, but this time we shall fully defined the problem, which practically means that the process of the change in the condition of the items considered will be defined. Instead of assuming the constant failure rate we shall specify the probability distributions of the time to failures of the corresponding items, as shown in the table below:

Now, we have fully specified the problem, but we do not have the fully defined algorithm for its solution, because the "classical" reliability theory and available national and international standards do not address this problem in spite of the fact that it exists

Table 1. Reliability data for the items considered.

Item	Distrbtn. of TTF	Parameters		MTTF	hazard function
A	Expntl.	$\lambda = 0.001$	/	1000	const.
B	Normal	$\mu = 1000$	$\sigma = 375$	1000	incrsn.
C	Weibull	$\eta = 790$	$\beta = 0.7$	1000	decrsn.

in every day engineering practice.

Hence, this paper will present the algorithm for solving this and any other problem of forecasting and calculating the reliability measures of complex engineering systems using the "bottom up" approach.

3. Reliability measures of a Single Engineering Item

In every day practice the occurrence of an uncertain event is described by the probability distribution of the chosen random variable through one of the well-known theoretical probability distributions. The most frequently used distributions for continuing random variables, in the area of reliability, maintainability and supportability engineering, are: exponential, normal, lognormal and Weibull [5]. Each of them represents a family of distributions where every member of the family is defined by some parameters, like: scale, shape and minimum value. Hence, if those parameters are specified the characteristics of probability distribution of the random variable like: expected value, $E(X)$; variance, $V(X)$; cumulative distribution function, $F(x)$; probability density function, $f(x)$ and others, are fully known.

It is necessary to say that the expected value, $E(X)$, defined by mathematicians means exactly the same as the mean time to failure used by the reliability practitioners. Thus, $X = TTF$, and $E(X) = E(TTF) = MTTF$.

Table 2 Illustrative example, input and output data in hours

Distrbtn.	Scale	Shape	MTTF	TTF_{10}	TTF_{50}	TTF_{90}
Expntl.	1000	0.00	1000	105	693	2303
Normal	1000	150	1000	810	1000	1195
	1000	300	1000	620	1000	1385
	1000	450	1000	455	1000	1615
Weibull	1000	1.00	1000	105	695	2303
	1115	1.59	1000	270	885	1884
	1126	2.67	1000	484	981	1539
	1100	4.22	1000	645	1008	1340

As the expected value is the subject of discussion generated by this paper, let us remember its general expression for the continuous random variable, say X:

$$E(X) = \int_0^\infty x \times f(x)dx \qquad (3)$$

where $f(x)$ is the probability density function of a random variable X. Applied to the time to failure, as a random variable, the above equation could be rewritten as [5]:

$$E(TTF) = MTTF = \int_0^\infty R(t)dt \qquad (4)$$

From the point of view of mathematics, $MTTF$ defined as above is fully known characteristic, but what does it mean to logistics engineers? Not a lot, because it only defines a single point of the probability distribution. In order to illustrate this statement, several examples are given and in Table 2, each of which exhibits identical mean time to failure of 1000 hours.

where; TTF_p represents the length of operation up to which 10, 50 and 90 percent of population will fail. The understanding of the behaviour of the random variable cannot be based on the information related to the expected value only. The last three columns in the above table clearly illustrates this statement.

The impact of the type of the distribution and values of scale and shape parameters on the reliability measures is illustrated by Fig. 1. Clearly, the differences are significant. For example, the values of the reliability function at 500 hours for all of them are scattered within a wide range of values (0.63 to 0.995). Certainly, there are an infinite number of reliability functions mean value ($MTTF$) of which is equal to 1000 hours, and each of them will have different values of reliability at different instances of operating time.

The main objective of the example used was to show that it is absolutely crucial to understand the process of change in the condition of the item in order to get a full picture about its reliability measures.

4. Reliability of Complex Engineering Systems

In the cases where the random variable analysed represents the complex event, its probability distribution depends on the probability of occurrence of consisting events. From the point of view of mathematics, the complex event is any event which consists of two or more related events. The probability of occurrence of the complex event depends on the relationship between consisting events. For example, if the complex event is defined as the intersection of two or more events then the probability of its

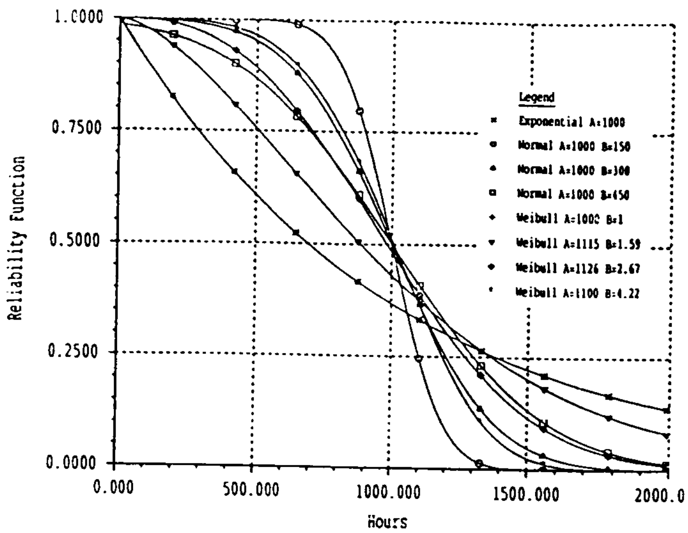

Figure 1. Reliability functions for several items with $MTTF = 1000$ hours

occurrence is equal to the product of probabilities of occurrence of consisting events. Making use of equation 2, the expression for the mean time to failure of the complex system which is defined by the complex random variable, $TTFs$, will be:

$$E(TTFs) = MTTFs = \int_0^\infty Rs(t)dt \quad (5)$$

where $Rs(t)$ is the reliability function of the complex system.

Clearly, the main problem facing the analyst is the determination of the reliability function of the complex system, $Rs(t)$.

In the case that the consisting items (items, units, components) are independent and connected in series, from the point of view of reliability, the reliability function of the system is defined as:

$$Rs(t) = \prod_{i=1}^{nci} Ri(t) \qquad (6)$$

where: nci is the number of consisting items, $Ri(t)$, reliability function of each consisting item representing the probability that the time to its failure is greater than t. Thus, the expression for the $MTTFs$ of the complex system could be obtained by combining equations 5 and 6, thus:

$$MTTFs = E(TTFs) = \int_0^{\infty} \prod_{i=1}^{nci} Ri(t)dt \quad (7)$$

The above expression can be used for the calculation of the mean time to failure of the system, $MTTFs$, which consists of any number of items, which are connected in series from the point of view of reliability, and whose failure rate could exhibit any pattern of the failure rate, i.e. any mixture of increasing, constant and decreasing.

In the cases where the analytical integration of the above expression is complicated, the required value could be obtained by using the graphical method.

5.IllustrativeExample

In order to illustrate the approach presented let as calculate the mean time to failure of the system whose consisting items are defined in Table 1.

Making use of equation 7, the mean time to failure of the system of 363 hours, was obtained by applying graphical method. This

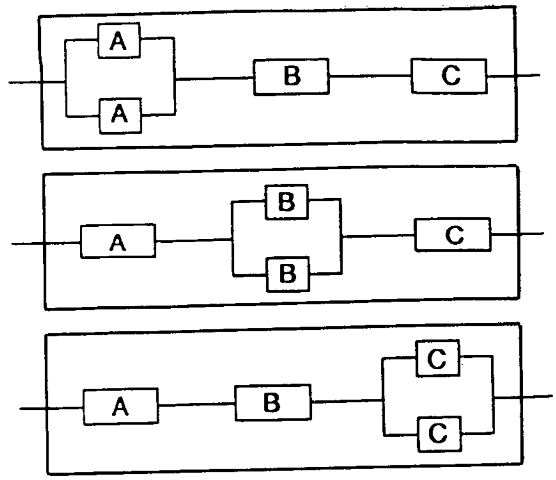

Figure 2. Possible configurations of the system

represents an increase of 10% in comparison with the corresponding value of 333.3 hours obtained by the "constant failure rate approach". The differences between these two approaches to the determination of the reliability measures are even more significant when they are used as a basis for the prediction of the demands for the logistic support resources.

Based on the practical experience and the illustrative example used it is extremely difficult to justify the use of the constant failure rate approach to the calculation of the reliability measures for the complex systems which consist of the mechanical, hydraulic, pneumatic, and similar items.

To illustrate further advantages of the method proposed, the situation where the increase of the reliability of the system is intended to be achieved by use of parallel configuration of two items of the same kind will be used, as shown in Figure 2.

Table 3. Reliability Analysis of Complex System

Config.	A	B	C	$MTTFs$	TTF^s_{10}	TTF^s_{50}	TTF^s_{90}
1	1	1	1	333	35	231	767
2	1	1	1	363	25	246	849
3	2	1	1	435	35	346	978
4	1	2	1	375	25	256	949
5	1	1	2	472	75	407	989
6	2	2	2	678	165	648	1241

In the case of the constant failure rate approach it is irrelevant which item, A, B or C, should be connected in parallel, because the $MTTFs$ will have identical. However, in all cases where the constant failure rate cannot be used as a model for the process of change in the condition of the consisting items, the above statement will be incorrect, as the Table 3 shows for the example used.

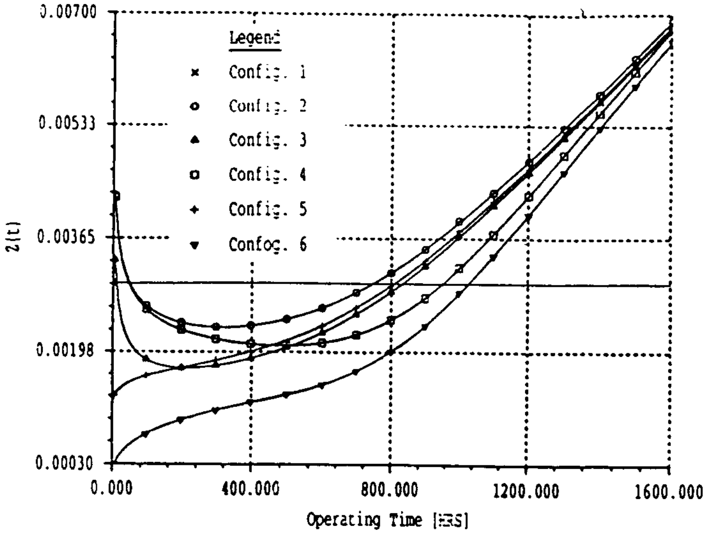

Figure 3. Hazard function of the system caused for different configurations of its items.

The usefulness of the reliability analysis to the design regarding the selection of the optimal configuration is obvious, especially in cases where due to weight, cost and space restrictions using a parallel configuration is very limited. The graphical representation of the pattern of the hazard function for each analysed configuration is given in Figure 3.

6.Conclusion

The main objective of the paper was to initiate a discussion on the accuracy of the determination of the estimated values of the measures of reliability and maintainability. The accurate way for calculating the expected value of the probability distribution of the random variable which represents the complex event has been demonstrated here. As a result of that, the accuracy of the mathematical models used by reliability, maintainability, and supportability engineers will increase and in consequence the credibility of the profession should increase among other engineering disciplines.

Based on several simple examples and brief theoretical analysis it is possible to learn the following lessons, from this paper:

a) The calculation of the expected value of the complex random variable cannot be based on the information related to the expected values of consisting events only. The type and parameters of the probability distributions of the consisting events are of crucial importance for the accurate results, as demonstrated;

b) The accuracy of the calculation of the expected values for the measures like: Mean Time To Failure, ($MTTF$), Mean Time Between Failure, ($MTBF$), and similar, could have crucial effects to the final results of the reliability analyses, especially in the cases of engineering systems which consist of several thousand components.

It is important to underline that the same conclusion is applicable to the calculation of the expected values of the random variables which describe other types of configurations of the system (parallel, mixed, m out on n) as well as measures of maintainability and supportability [2].

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Mission Success Driven Space System Sparing Analysis

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Abstract

Among the maintenance resources, the spare parts are the most difficult to predict. Items in the space systems are very different from the point of view of reliability, cost, weight, volume, etc. The different combinations of spares make different contribution to the: mission success, spare investment, volume occupied and weight. Hence, the selection of spares for a mission planned must take into account all of these features. This paper presents the generic mission success driven sparing model developed, for the complex space systems. The mathematical analysis used in the model enables the user to select the most suitable selection of the spare package for the mission planned. The illustrative examples presented clearly demonstrate the applicability and usefulness of the model introduced.

1. Introduction

The main objective of any space system is to fulfil required mission. In majority of cases during the operational mission of repairable space systems the lead times for obtaining the replenishment are very long and often impossible. Thus, to ensure the accomplishment of the space mission, all the logistic support resources necessary for the completion of maintenance tasks required must be carried with the space vehicles along their missions. Due to the limitations on the load and space, it is impossible to carry as much resources as one would like to 'double' ensure the provision of these resources. Clearly, the accurate estimation of resources needed is of the great importance for the successful completion of space missions.

The sparing problem related to the spares stocked at the base has been well addressed by the models in literature and the commercial software. However, the sparing for the successful completion of an space mission has not yet been analysed as a specific problem. Furthermore, the methods for the determination of the quantity of spares used by the existing sparing models are based on constant failure rate. In reality, the behaviour of items can be modelled by any type of well-known probability distributions, which means that the failure rate could be increasing or decreasing function of the length of operational time. Consequently, the application of the constant failure rate behaviour to all items could lead to significant error.

The aim of the paper is to present the model for the determination of the number of spares required for the successful completion of the mission planned, based on the criteria like, the required availability, costs, weight and similar, which is also able to cope with the cases where the behaviour of the items during the operation could not be modelled by the constant failure rate approach.

From logistic point of view, all consisting items of a repairable system could be discarded or repaired, after their failures. This paper, for the sake of simplicity, focuses on the sparing for discard items. The similar analysis method can be applied to repairable items.

In order to address the sparing problem fully, it is assumed in this paper that all the other resources needed are available as called. Consequently, the spares are the only factor that has primary effect on the mission completion.

2. Measures of Space Mission Success

During a mission of the system, the failure/restoration cycle is repeated until the accomplishment of the mission, given that the resources needed for the maintenance are sufficient enough. Otherwise, the termination of the mission could be required before its completion.

Due to the randomness of the occurrence of failures, the successful completion of a space mission is a probabilistic event. Hence, the mission success, MS can only be quantified through the probability. In the case that n spares are stocked on the board, the space mission will be accomplished if less than or equal to n failures occurred. Hence, the probability of mission success is just the probability that the cumulative number of failures during the mission is less than $n+1$. Thus, the criterion for the determination of the quantity of spares for this type of missions could be defined as the probability that the total number of failures is less than $n+1$.

3. Sparing Model for a Single Item

Considering a single item the following assumptions are made:

1) the time to failure of the item is modelled by *pdf* $f(t)$, whose CDF is $F(t)$, which can be represented by any type of probability distribution;

2) the length of the mission is T_m;

3) at the beginning of the mission the total amount of n spares are supplied;

4) no replenishment spares will be obtained during the mission;

5) the time to replace the failed item is much less than the length of the mission so that the replacement can be viewed as instant.

The main question is how many spares are needed for the successful completion of the mission planned?.

The probability of the mission success, in this case, is equal to the probability that the Number of Failures during the mission, $NF(T_m)$, is less than or equal to the number of spares, n. This is, of course, the function of the length of mission, T_m, and the number of spares, n, and denoted as $MS(T_m, n)$, thus :

$$MS(T_m, n) = P(NF(T_m) \leq n). \quad (1)$$

According to renewal theory [1], the probability that the number of failures in time T_m is less than or equal to n can be expressed as following:

$$P(NF(T_m) \leq n) = 1 - F^{n+1}(T_m), \quad (2)$$

where $F^{n+1}(t)$ is the $(n+1)$ fold convolution, defined as:

$$F^{n+1}(t) = \int_0^t F^n(t-u)\, dF(u) \qquad (3)$$

and $F^1(t)$ is $F_1(t)$ defined in (2). Thus,

$$MS(T_m, n) = 1 - F^{n+1}(T_m). \qquad (4)$$

For the required Mission Success, MS^r, the number of spares required, n^r, to be carried along with the mission can be determined as follows:

$$n^r = \min_n \{n | MS(T_m, n) \geq MS^r\}. \qquad (5)$$

For the hypothetical three items the mission success have been calculated and the results obtained is presented in the following table.

Item	1	2	3
Distribution	Exponential	Normal	Weibull
A	500	500	54
B	-	150	0.3
$MTTF$	500	500	500
$MTTR$	50	50	50
T_m	1000	1000	1000
n	$MS(n)$	$MS(n)$	$MS(n)$
0	0.0005	0.00000	0.0000
1	0.3135	0.4971	0.4122
2	0.6264	0.9702	0.6641
3	0.8349	0.9994	0.8132
4	0.9392	0.9999	0.8988
5	0.9809	1.0000	0.9466
6	0.9948	1.0000	0.9725
7	0.9987	1.0000	0.9862
8	0.9997	1.0000	0.9932
9	0.9999	1.0000	0.9967
10	1.0000	1.0000	0.9985

where: n, represents the number of spares at the beginning of the mission, $MS(n)$ is the Probability of mission success, given n spares at $t = 0$. The above data clearly show that the spare requirements satisfying the same MS are of significant difference resulting from the different failure time distributions, and that, in particular, the constant failure rate assumption, i.e. exponential distribution, adopted by conventionally used method for sparing causes remarkable error due to ignoring the true distribution of the item's failure time distribution, govern by the mechanism of failure.

4. Optimal Sparing Model for a System

The objective of sparing for a space mission is to optimally determine the quantities of spares for each reliability critical item in the system to ensure the accomplishment of the mission, whilst the specified optimisation target, such as cost and weight, imposed upon spares can be achieved. This problem is usually known as optimal spare allocation.

The optimal spare allocation problem is solved in existing commercial model by using constant failure rate method [3][4]. However, this method is not really optimal. In [5] a dynamic programming model to minimise the total spare cost subject to the required availability has been presented in [5]. For the space mission, in some cases, the total weight or the total volume is the major concern in sparing analysis. In this section, the dynamic programming technique has been used in order to solve the optimal spare allocation problem, which is: to minimise the total weight of spares subject to the required probability of space mission success.

4.1 Dynamic Programming Model

Suppose that the system under consideration consists of n items, all items are mutually independent and connected in series from the reliability point of view. Let W_i denote the total weight of spares for item i, P_i the achieved probability of mission success of item $i, and P_s$ the required probability of mission success of the system. The optimisation problem indentified above can be formulated as follows :

$$\min \sum_{i=1}^{n} W_i \tag{6}$$

subject to

$$\prod_{i=1}^{n} P_i \geq P_s \, . \tag{7}$$

Equations 6 and 7 represent the target function, and constraint of the problem, respectively.

This problem is converted to a dynamic programming model. where the following notations are adopted, for each item $i, (i = 1, \ldots, n)$, and the system:

d_i : decision variable
D_i : decision space
s_i : state variable
S_i : state space
$P_i(k)$: mission success probability with respect to k spares available
W_i : total spare weight
W_{oi} : unit spare weight
$R_i(.)$: return function
$F_i(.)$: optimal return function

The parameters in the D.P. model are specified as below:

1) Stage i : each item of the system is defined as a stage. There are n stages altogether in the model;

2) Decision variable d_i : the number of spares allocated to the ith item at stage $i, i = 1, \ldots, n$;

3) State Variable, s_i: the probability of mission success of the part of the system from item n up to item $i+1$; Note that s_n , the state variable at stage n, is equal to one. The transfer function can be expressed as below:

$$s_{i-1} = s_i \times P(d_i), \quad i = 1, \ldots, n, \tag{8}$$

where $P(.)$ is equation (7). Thus, state variable s_0 is just the mission success probability of entire system.

4) Return function, $R_i(d_i)$: Each value of decision variable indicates possible spare number allocated to an item. The return from decision is defined as the total spare weight of the item:

$$R_i(d_i) = W_{oi} \times d_i, i = 1, \ldots, n. \tag{9}$$

5) Optimal Return Function of Stage i, $F_i(s_i)$: the optimal value of cumulative spare weight from stage 1 up to stage i, which can be defined as follows :

$$F_i(s_i) = \min_{d_i}[R_i(s_i) + F_i - 1(s_i - 1)]. \tag{10}$$

Item	1	2	3
Unit Weight	1.5	1	2

n	Item-1		Item-2		Item-3	
	MS	W	MS	W	MS	W
3	-	-	0.9895	3	-	-
4	-	-	0.9998	4	-	-
5	0.9809	7.5	1.0000	5	-	-
6	0.9948	9	-	-	0.9803	12
7	0.9987	10.5	-	-	0.9906	14
8	0.9997	12	-	-	0.9956	16
9	0.9999	13.5	-	-	0.9980	18
10	1.0000	15	-	-	0.9991	20
11	-	-	-	-	0.9996	22
12	-	-	-	-	0.9998	24

Due to the limitation of the size of the paper, the algorithm of implementing the model is left out. Readers who are interested in it can refer to [5].

The following example demonstrates the application of the above D.P. model for optimal allocation of the mission spare.

Considering the hypothetical items defined in Table 1, the unit weight of each is given below:

The objective of the example is to minimize the total weight of spares, while the system's probability of the mission success probability of 0.98 is to be met. The feasible value of number of spares and associated $MS(n)$ and weight for each item are listed as below:

The results of spare requirement allocated to each item are in the following:

Item	1	2	3	System
n	6	4	7	-
MS	0.9948	0.9998	0.9906	0.9853
W	9	4	14	27

5 Conclusion

This paper addresses the problem of sparing analysis driven by the mission success. Firstly, the measure of mission success, namely the probability of mission success was defined, which forms the criteria for sparing optimisation. Secondly, the mission sparing model for a single item was developed in terms of failure time distribution instead of constant failure, which is conventionally applied, by using renewal theory. Finally, the dynamic programming model for the optimal spare allocation to the entire system was developed, where the weight of spares was used as the decision criterion.

The model developed and the examples cited shown that the type of the failure time distribution and its parameters have strong influence on the solution of sparing analysis, which constant failure rate method ignores. Consequently, the calculation of spare requirement by the model developed is significantly improved.

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A Simple Space Station Rescue Vehicle

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ABSTRACT

Early in the development of the Space Station it was determined that there is a need to have a vehicle which could be used in the event that the Station crew needed to quickly depart and return to Earth when the Space Shuttle is not available. Unplanned return missions might occur because of a medical emergency, a major Station failure, or if there is a long-term interruption in the delivery of logistics to the Station. The rescue vehicle was envisioned as a simple capsule-type spacecraft which could be maintained in a dormant state at the Station for several years and be quickly activated by the crew when needed.

During the assembly phase for the International Space Station, unplanned return missions will be performed by the Russian Soyuz vehicle, which can return up to three people. When the Station assembly is complete there will be a need for rescue capability for up to six people. This need might be met by an additional Soyuz vehicle or by a new vehicle which might come from a variety of sources. This paper describes one candidate concept for a Space Station rescue vehicle. This concept was developed by engineers at the Johnson Space Center.

The proposed rescue vehicle design has the blunt-cone shape of the Apollo command module but with a larger diameter. The rescue vehicle would be delivered to the Station in the payload bay of the Space Shuttle. The spacecraft design can accommodate six to eight people for a one-day return mission. All of the systems for the mission including deorbit propulsion are contained within the conical spacecraft and so there is no separate service module. The use of the proven Apollo re-entry shape would greatly reduce the time and cost for development and testing. Other aspects of the design are also intended to minimize development cost and simplify operations. This paper will summarize the evolution of rescue vehicle concepts, the functional requirements for a rescue vehicle, and describe the proposed design.

PURPOSE OF THE RESCUE VEHICLE

The International Space Station has a multi-year mission during which many astronaut and research crew members will occupy the Station. The crew members will reach the Station in the Space Shuttle, Soyuz spacecraft, or other crew transport vehicles. The Station and its crews will be dependent on the regular delivery of supplies by the Shuttle and other transport vehicles. The transport vehicles will arrive and depart on predetermined schedules. It will be difficult in the case of the Soyuz and even more difficult in the case of the Shuttle, to launch a mission with crew or supplies ahead of schedule.

It was recognized early in the Space Station development program that a situation might develop in which a crew member might need to be transported to the ground ahead of schedule because of a serious illness or injury. Also, a serious system failure aboard the Station might make an immediate evacuation and return to Earth necessary. Finally, if a launch vehicle failure occurred, the interruption of supply deliveries might require the eventual evacuation of the Station crew in a vehicle other than the one which failed. These three scenarios correspond to the three missions for a Space Station rescue vehicle:

- medical evacuation
- immediate return in case of a Space Station failure
- return in case crew rotation and re-supply are interrupted by a launch system failure

A variety of means for providing emergency crew return were considered by the Space Station Program. The option of keeping a Space Shuttle Orbiter docked at the Station for the entire crew rotation period has many advantages but requires that the Orbiter be modified for long duration flight. The option of maintaining a Space Shuttle on standby for immediate launch to the Station in an emergency was deemed to be impractical. Co-orbiting vehicles and safe-haven concepts were considered too complicated and costly. It was concluded that a separate vehicle, docked to the Station at all times, was the most effective means of providing emergency crew return capability.

It should be noted that in the operation of the Salyut and Skylab space stations, the transport vehicle for the crew always remained docked to the Station so it was available for use by the crew at any time. The current Mir station is also operated in this manner. In the case of the International Space Station, the Space Shuttle will remain docked for short times but leave crews onboard when it departs. The Soyuz spacecraft, with three seats, will be used by the Russians for crew transport and will remain docked as long as the crew is present. The Soyuz therefore provides immediate return capability which is sufficient during the assembly phase when the number of crew will not exceed three unless the Shuttle is present.

Following the assembly phase, the normal Station crew number is expected to be six. Assuming that three people can be returned in the Soyuz that is always present for Russian crew rotation, there is still a need for rescue capability for three more people. The additional rescue capability could be provided by having two Soyuz present or by adding another rescue vehicle.

The use of two Soyuz vehicles to provide complete rescue capability remains a viable option for the Space Station. Other approaches continue to be considered because of some limitations in Soyuz capability. The Soyuz is designed for a service life of six months and would require replacement at a rate that exceeds that required for Russian crew rotation. This implies that an extra Soyuz spacecraft would have to be manufactured and flown to the Station every six months for the purpose of providing rescue capability.

Another limitation is that the American astronaut population currently includes many members who exceed the Soyuz height limit of 182 centimeters. For descent in the Soyuz, all occupants wear pressure suits which could restrict the ability to return a seriously ill or injured crew member. The very limited internal volume and compact seating arrangement in the Soyuz also limit its effectiveness for medical evacuations.

Some modifications to make the Soyuz more compliant with rescue vehicle requirements have been under consideration and these changes, if implemented, would increase the possibility of using Soyuz spacecraft as rescue vehicles throughout the lifetime of the Space Station. However, because of the uncertainties about the potential modifications and long-term availability of the Soyuz, other options have continued to be considered.

CONCEPT EVOLUTION

During the period of Space Station development, a number of rescue vehicle concepts have been developed. Several design studies that influenced the design in this paper should be noted. One of the first Station rescue vehicle concepts which was developed in 1986 by an engineering team at the Johnson Space Center was a six-person Apollo-shaped spacecraft with a 4.4-meter diameter and a separate service module (Reference 1). Soon after that another team developed a concept which came to be known as the SCRAM. The SCRAM design has a cylindrical pressure vessel for six people sitting on a conical heatshield (Reference 2). Later the SCRAM concept was modified to accommodate eight people (Reference 3).

In 1992, in response to a request from NASA management, a concept was developed for a two-way crew transport with the groundrule that the development would be done by civil service employees using government facilities as much as possible. This "in-house" approach was emphasized in an effort to minimize the eventual cost of the spacecraft. The concept developed in this study was a four-person Apollo-shaped vehicle with a separate service module. As a crew transport, the spacecraft would be launched on an expendable launch vehicle and it carried an Apollo-type launch escape rocket (Reference 4). In 1994, the two-way transport design was adapted to the requirements of a one-way Station rescue vehicle which resulted in the design described in Reference 5 and in this paper. As part of the design studies for the "in-house" crew transport and rescue vehicles, the team defined a detailed development plan including all engineering activities from concept definition to delivery of the flight units. This development plan was the basis for a comprehensive schedule and cost estimate including all labor and materials.

STUDY GROUNDRULES

The specific design concept described here was intended to meet all the basic requirements for a Space Station rescue vehicle and was also developed with some unique groundrules:

- Development work would be performed by civil service personnel using government facilities as much as possible
- The spacecraft would be delivered to orbit in the payload bay of the Space Shuttle
- Ocean recovery would be acceptable
- Reusability would not be required
- The conceptual design would include the definition of the complete development and fabrication process and a detailed costestimate
- Two operational spacecraft would be built
- There would be an orbital flight test

FUNCTIONAL REQUIREMENTS

Missions: The purpose of the rescue vehicle is to return Space Station crew members in case of a medical emergency, a Space Station failure which requires immediate evacuation, or the lack of availability of the Space Shuttle for a normal return. The spacecraft must separate from the Station, loiter in-orbit for up to 24 hours, perform a deorbit maneuver, descend through the atmosphere, and land safely.

Capacity: Six to eight people with minimal provisions.

Duration: 36 hours in an active mode (24 hours for loiter, deorbit and landing plus 12 hour margin) 5 years docked to the Station in a quiescent mode, using power from the Station (continuous Station power requirement should not exceed 300 watts.)

Operations: Automatic operation for all functions with manual intervention possible for some critical functions

Delivery to Orbit: The spacecraft will be delivered to the Space Station in the payload bay of the Space Shuttle Orbiter. A support structure for this purpose must be defined.

Berthing: The spacecraft must accommodate berthing by a remote manipulator to a berthing port on the Space Station and therefore must have a grapple fixture and a berthing mechanism. Active rendezvous and docking is not required.

Cabin Atmosphere: Standard oxygen and nitrogen mixture at 1 atmosphere. Pressure suits will not be worn by personnel for descent. Extra-vehicular activities are not required.

Communications: Two-way communication for voice, telemetry, and commands with the Space Station and the ground control center is required.

Recovery: The primary mode is water recovery at a coastal site near the Kennedy Space Center. There should be backup water sites. Emergency land impact must be survivable.

Safety: All systems are fail-safe for crew return or designed with adequate safety margins where redundancy is not practical.

Mission Timeline: The mission is planned for normal recovery at a coastal water site near the Kennedy Space Center (KSC). A typical mission timeline is provided below.

Hrs:min	
00:00	Separation from Space Station
01:45	Deorbit for first landing opportunity to KSC site
02:30	Landing and recovery
02:45	Deorbit for second landing opportunity to KSC site (contingency)
24:45	Deorbit for third landing opportunity to KSC site (contingency)

Velocity Increment:

Separation	1.0	meter/second
Deorbit	119.0	meters/second
Total	120.0	meters/second

CONCEPT CONFIGURATION

The rescue vehicle concept is shown in Figure 1 and described below. A dimensioned drawing of the crew module segment is shown in Figure 2.

Structure and Thermal Protection: The exterior shell of the crew module is the same shape as the Apollo command module. However, its base diameter is increased to 4.42 meters (14.5 ft) to provide greater volume. This diameter will still allow the crew module to fit within the payload bay of the Space Shuttle.

The primary structure is an aluminum-2219, skin-stringer construction. The pressure vessel is a separate structural assembly of welded aluminum-2219 located inside the exterior shell of the crew module. For thermal protection, the base of the crew module is covered with ceramic tiles which are similar to the tiles on the Space Shuttle Orbiter. The conical section is covered with flexible blanket insulation which is similar to the material on the Shuttle Orbiter upper surfaces.

The crew module has windows and a side hatch which are similar to the Apollo command module. The transfer tunnel at the apex is a scaled-up version of the Apollo design. In order to be compatible with the docking port on the Space Station, a separate docking adapter is attached to the transfer tunnel. In this design the docking mechanism is the Androgynous Peripheral Attachment System (APAS). In an emergency mission, the spacecraft would separate from the docking adapter when departing and the adapter would remain attached to the Station.

The spacecraft structure must include a grapple fixture so that a remote manipulator can remove the spacecraft from the Shuttle payload bay and attach it to the docking port on the Space Station.

Propulsion: The crew module propulsion system provides attitude control and is used for the deorbit maneuver. It is a unique feature of this design, compared to other capsule concepts, to include the deorbit propulsion capability in the crew module rather than adding a separate service module. The relatively large volume of the crew module makes this possible. The benefits of this feature are a major reduction in vehicle interfaces, the opportunity to recover and reuse the propulsion system components, and the elimination of service module impact concerns which greatly expands landing zone options.

The propulsion system is based on the Apollo command module design with two additional thrusters. There are fourteen pressure-fed bi-propellant thrusters with scarfed nozzles. Each thruster develops a vacuum thrust of 445 Newtons (100 pounds-force). The propellants are monomethyl-hydrazine and nitrogen tetroxide stored in eight tanks.

Power: Since the vehicle is delivered as a payload by the Space Shuttle and may remain attached to the Station in a dormant state for several years, reserve batteries are used. These batteries are not activated until needed at the time of an emergency mission. External power from the Space Station would be used for thermal control, status monitoring, and periodic checkout but that power requirement is not expected to exceed 300 watts. The maximum power level for the rescue vehicle, when activated, is estimated to be a little more than 3 kilowatts. The design has 16 battery modules packaged in two units. The power distribution system includes control units and conversion units to provide alternating current as well as direct current at 28 volts. There are two main direct current buses and two alternating current buses.

Avionics: The rescue vehicle must provide its own capability for navigation and communications. The design includes an integrated inertial navigation system and star trackers. There are also global positioning system (GPS) receivers and antennas. The avionics sensors are linked to general purpose computers which communicate to other components, including the attitude control jet drivers, through multiplexer-demultiplexer units.

Displays and Controls: There is a caution and warning system to monitor the major crew module systems and alert the crew through audio tones and warning lights if there are problems. All spacecraft functions are automated but there are provisions for crew intervention in critical functions. There is a limited set of approximately 20 circuit breakers and 20 switches, but most of the crew interaction with systems is through multi-function electronic display screens and programmable pushbutton panels. There is also a rotational hand controller and a translational hand controller for manual maneuvers.

Communications: The crew module has UHF and S-band radio systems for communication with the ground. There is a search and rescue communication system (SARSAT) for use after landing and a set of personal handheld radios for emergency use after landing. An audio system in the crew module provides for voice communication through individual headsets and speakers.

Life Support and Active Thermal Control: Oxygen for breathing is provided from storage tanks and nitrogen is available for re-pressurization if needed. Carbon dioxide is removed from the cabin air with lithium hydroxide (LiOH) canisters. A fan circulates cabin air and provides for air flow through the lithium hydroxide canisters.

There is a cabin air heat exchanger which also controls cabin humidity. All system components which generate heat are mounted on cold plates which are cooled by circulating water. Waste heat is rejected by a water flash evaporator system.

Landing: The crew module is decelerated during descent by a drogue parachute and then a cluster of three large ring-sail parachutes. The diameter of each parachute is 26 meters. The expected velocity at impact is 7.6 meters/second. After landing in the water, flotation bags, similar to those used on the Apollo command module, will be inflated to ensure that the crew module is turned upright and remains upright during the recovery phase. A diagram of the main parachute cluster is shown in Figure 3.

Land recovery using a deceleration system might be achieved with a moderate increase in development cost. Compared to water recovery, land recovery is in some ways safer, recovery operations are less costly, and reuse of hardware is more practical.

Pyrotechnic Devices: There are pyrotechnic devices associated with the following systems and interfaces:
- propellant isolation valves
- docking mechanism emergency separation
- parachute system cover and parachute deployment
- flotation system.

Crew Accommodations: The crew module can have up to eight couches to accommodate the crew members during descent. The couches are supported by attenuating struts which reduce the impact acceleration at landing. The crew members will not wear pressure suits. Additional provisions include drinking water, food, equipment for food preparation, personal hygiene, waste management, and emergency survival.

Accommodation in Space Shuttle Payload Bay: The rescue vehicle will be delivered to space station in the Space Shuttle and may need to return in the Shuttle in the case of a launch abort or for refurbishment after its operational life is exceeded. In either case, it requires support structure to secure it in the payload bay during launch and landing.

The attach structure concept involves two longeron trunnions and one keel trunnion attached directly to the spacecraft just forward of the heat shield to support the mass of the crew module. The trunnions will be attached to standard payload bay latches and bridges. The docking adapter at the forward end of the spacecraft would be "docked" to a simulated docking mechanism on its own support structure in the payload bay as shown in Figure 4.

The forward support structure, along with the simulated docking mechanism, would remain in the payload bay following deployment. It could be used on future refurbishment missions to bring back the rescue vehicle. Because of its relatively compact volume, there will be enough room in the payload bay to return other payloads from the station after the rescue vehicle is removed.

It was assumed that the Space Shuttle remote manipulator will be used to unlatch and remove the vehicle from the payload bay. The grapple fixture will be located on the docking adapter assembly.

Mass Properties: A three-dimensional computer solid model was used to investigate various crew module configurations and to estimate center of gravity and moments of inertia. Eight people can be located inside the crew module, although 6 or 7 people could be accommodated more comfortably. The vehicle center of gravity and moments of inertia were calculated from the masses of individual components modeled in the computer solid model. The mass estimate for each major subsystem is shown in Table 1.

DEFINITION OF DEVELOPMENT PLAN

The cost estimates for labor and materials and the detailed development schedule produced in this study are considered sensitive information and are not included in this paper. However, the process followed in preparing the estimates is summarized below.

The first step in preparing the cost estimate is to define all of the development activities. In the original two-way personnel transport vehicle study (Reference 4), technical specialists in each area defined all of the activities which must be done, how long each activity would take, how many people would be required to perform the activity, and what materials, equipment, special skills, and facilities would be required. For the rescue vehicle study, these technical specialists were contacted again to determine changes to their former estimates to reflect the difference in the mission and vehicle. The work breakdown structure includes all of the spacecraft technical disciplines as well as systems engineering and integration functions for all phases of the program.

All phases of the development program were considered from requirements definition and conceptual design through fabrication and testing of the qualification and flight units. Approximately 900 activities were defined. Requirements for material and personnel travel were also identified. All of the development activities were integrated into a master schedule. Resource estimates were based on vendor information, previous experience, and other programs.

All activities were arranged in a logical sequence and some optimization was done to control the duration of the schedule. The critical path includes those activities which drive the overall length of the schedule. Structural design, fabrication, and assembly are the most significant activities on the critical path, however activities related to propulsion, avionics, electrical power, and thermal protection systems also appear on the critical path. The experience gained at the Johnson Space Center in the in-house fabrication of a structural article for the Aero-assist Flight Experiment project provided the analogy for schedule estimates for structure and thermal protection system fabrication and assembly.

The following tests were included in the schedule and cost estimates:

- Subsystem and qualification tests for all components
- Static structural tests
- Vibro-acoustic tests
- Thermal-vacuum tests
- Electro-magnetic interference tests
- Landing impact tests (drops from test stand)
- Air-drop tests for the landing system (from aircraft)
- Water stability tests
- Water recovery tests
- Crew operations evaluations
- Docking mechanism tests
- Integrated crew module tests
- Shuttle cargo integration
- Orbital flight test

The following hardware for the development and test program was included in the estimate (including spares):

- At least two equivalent units for each subsystem
- 6 crew module structural prototypes ("boilerplates")
- 1 crew module mockup for operations evaluations

CONCLUSION

A conceptual design was developed for a spacecraft which could provide rescue capability for the International Space Station. The features of this vehicle which make it attractive as a simple rescue vehicle are:

- use of the proven Apollo re-entry vehicle shape which reduces the need for extensive aerodynamic analysis and testing
- increased volume with the capacity for up to eight people while also accommodating all support systems within the crew module
- elimination of a separate, expendable service module which greatly reduces the number and complexity of interfaces and permits the selection of landing sites without concern about service module debris impact
- separate docking adapter which allows for flexibility in the allocation of docking ports for the rescue vehicle without forcing a vehicle or Station design change and also allows for return and reuse of the expensive docking mechanism
- payload bay support system which allows for delivery and return of the rescue vehicle with minimal impact on other Shuttle cargo operations

Based on the engineering plan completed as part of the design study, development and fabrication of the vehicle as an in-house project at the Johnson Space Center appears feasible. The skills required have been identified and are available within the existing workforce at the Center. The fabrication techniques required are within the capabilities of the Center and the facilities and equipment are generally available. The actual availability of personnel for such a future project is difficult to predict since it depends on the level of support required for other on-going programs. However, the in-house approach should minimize the overall manpower required to complete this project. In comparison to the traditional NASA contracting approach, significant cost savings are expected with the in-house approach proposed in this study since much of the labor for procurement, contract management, and technical oversight is eliminated. Alternatively, the design concept would also be compatible with a fixed-price procurement approach.

In addition to serving as a Space Station rescue vehicle, the spacecraft concept described in this paper could be evolved for other applications such as a two-way Earth-to-orbit crew transport, an unmanned logistics carrier, or a re-entry capsule for lunar and planetary spacecraft. The design was based on the use of current technology systems and so there is great potential for improving the design by introducing more advanced systems in the future.

ACKNOWLEDGMENTS

The design study described in this report is the result of a coordinated effort by a team, representing most of the organizations at the Johnson Space Center and the author would like to acknowledge their contributions. The development plan, schedule and cost estimates for this design were compiled and integrated by Brent Scheffer. Jim Masciarelli is responsible for much of the design integration. The team also included: Mary Cerimele, Ann Bufkin, Joe Riccio, Chris Madden, John Ruppert, David Pruett, Marybeth Edeen, Mike Hoy, Steve Munday, Richard Hill, John Trainor, Randy Rust, John Zipay, Lawrence Turner, Chris Brown, June Hoang, James Keiser, Laurie Weaver, Kevin Templin, Barbara Dubcek, Jerry Borrer, Carl Meade, Michelle Munk, Nancy Tengler, George Ladrach, and George Sandars. Charles Teixeira provided management oversight of the design study.

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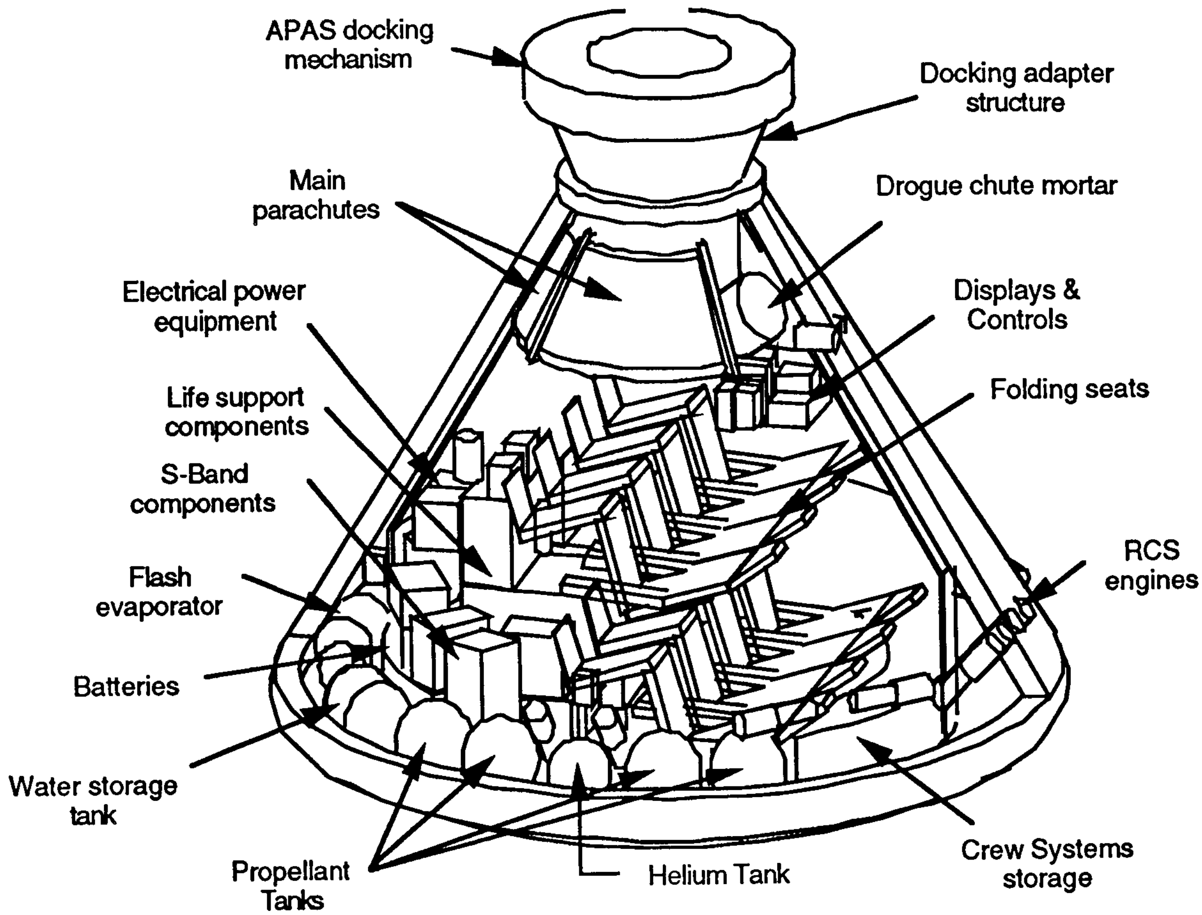

Figure 1: Cutaway View of Rescue Vehicle

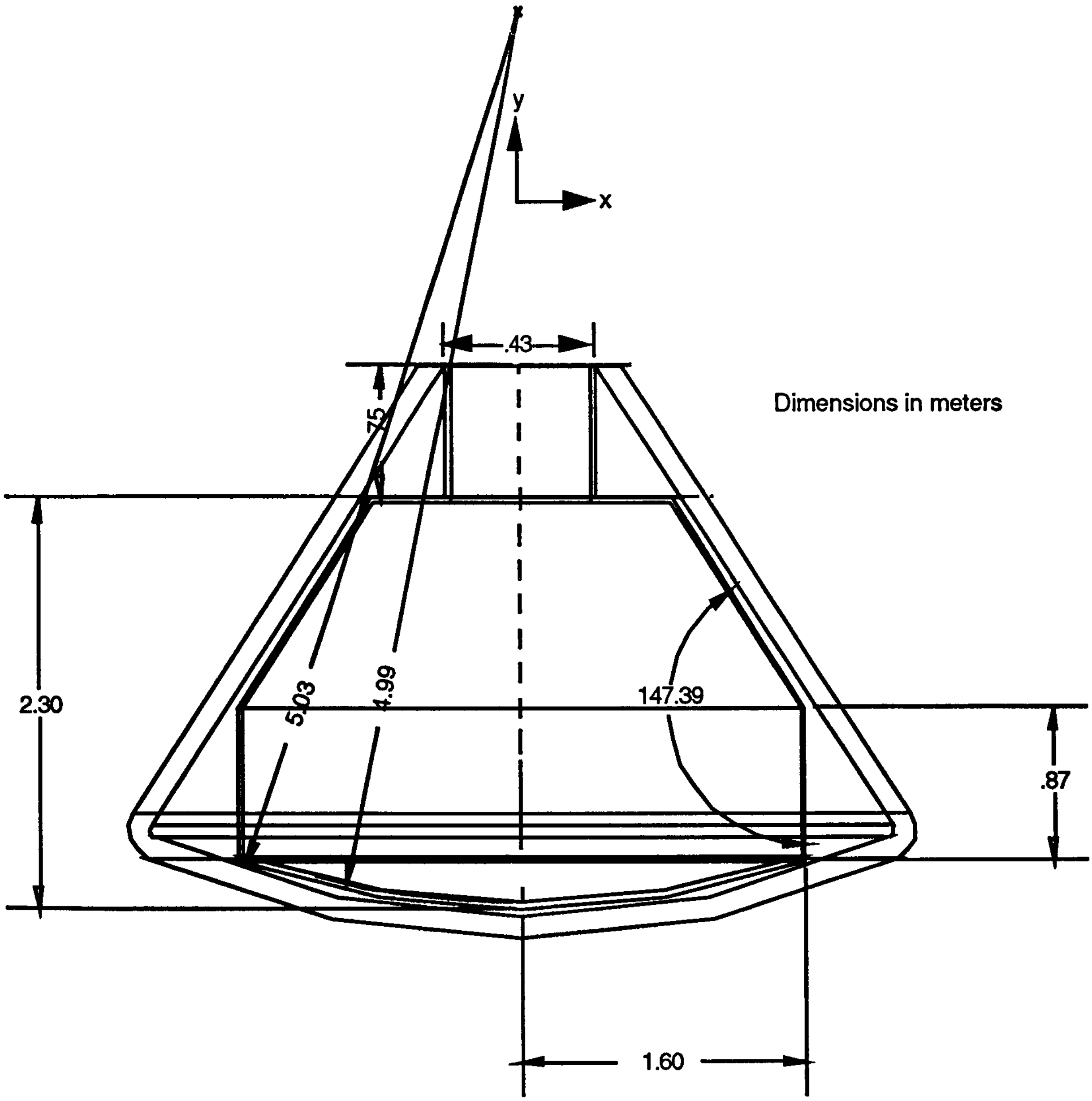

Figure 2: Rescue Vehicle with Dimensions (Docking Adapter not included)

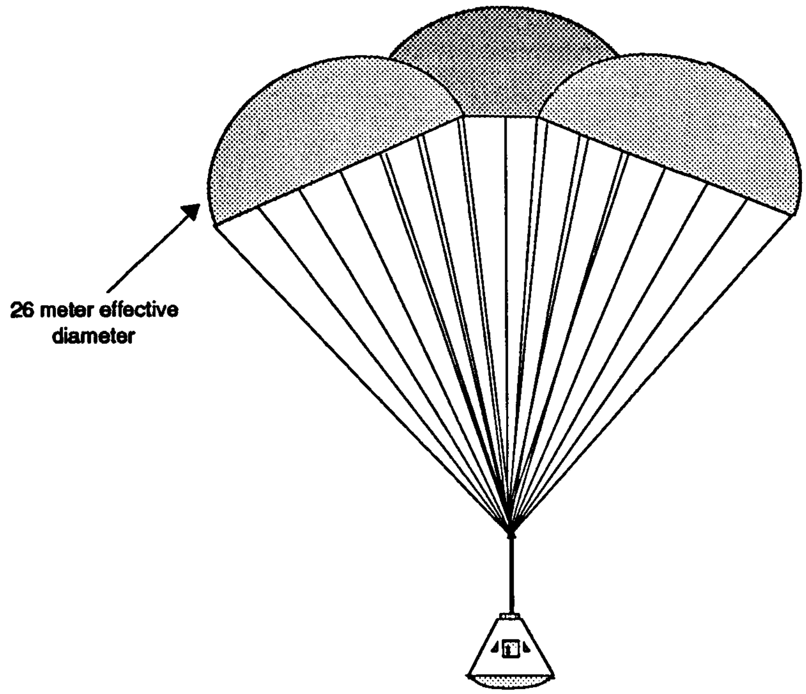

Figure 3: Rescue Vehicle Landing System

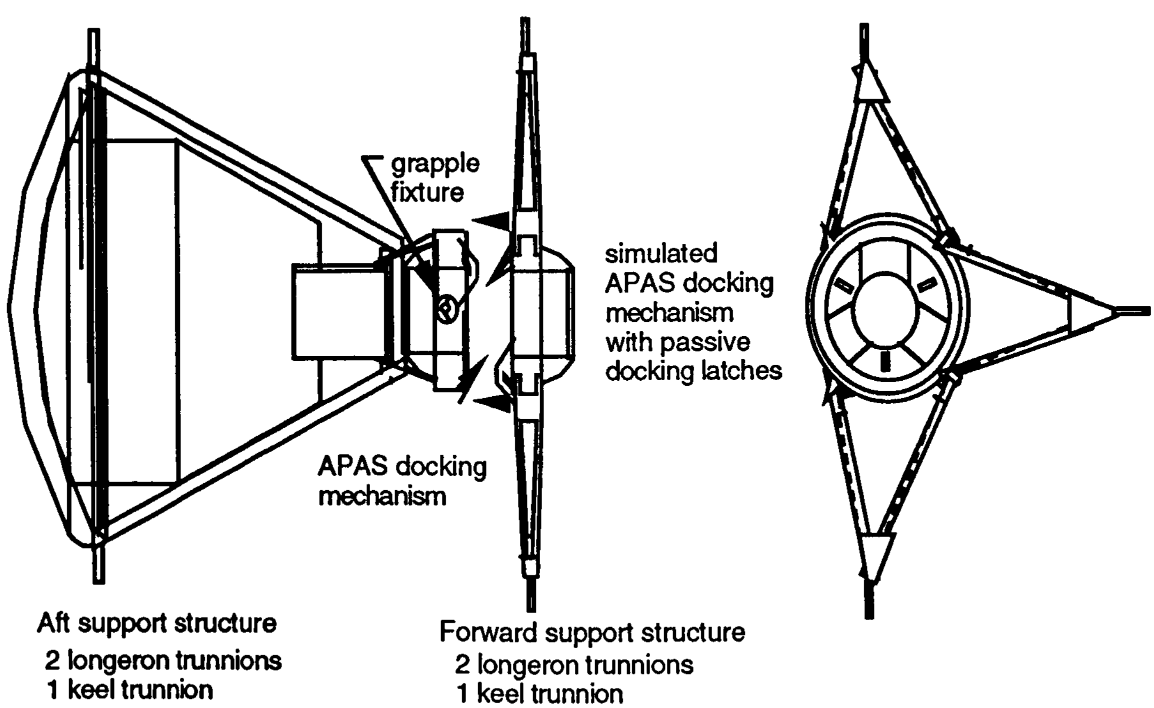

Figure 4: Payload Bay Support Structure

Table 1: Rescue Vehicle Concept Mass

Functional Area	Crew Module	Docking Adapter	Shuttle Support
Structure	488	91	591
Thermal Protection	861		
Propulsion	136		
Power	884		
Control	91		
Avionics	475		
Environment	339		23
Landing & Pyros	449	365	523
Crew Accommodations	436		
Weight Growth	624		
DRY MASS (kg)	4783	456	1137
Cargo	0		
Crew & Provisions	1240		
INERT MASS (kg)	6023	456	1137
O2, N2, Water, LiOH	105		
Propellant	308		
GROSS MASS (kg)	6436	456	1137
Total mass to launch in Shuttle			8029 kg

AIAA-95-0915-CP

INTERNATIONAL SPACE STATION ALPHA (ISSA) INTEGRATED TRAFFIC MODEL

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Abstract

The paper discusses the development process of the International Space Station Alpha (ISSA) Integrated Traffic Model which is a subsystem analyses tool utilized in the ISSA design analysis cycles. Fast-track prototyping of the detailed relationships between daily crew and station consumables, propellant needs, maintenance requirements and crew rotation via spread sheets provide adequate bench marks to assess cargo vehicle design and performance characteristics.

Nomenclature

APCU	Auxiliary Power Control Unit
ATV	Automated Transfer Vehicle
CAP	Capability
CV	Cargo Vehicle
COTS	Commercial off-the-shelf software
ECLSS	Environmental Control and Life Support System
ESA	European Space Agency
EXT_AL	Weight of external airlock
FSE	Flight Support Equipment
JSC	Johnson Space Center
H_2O	Water
IPT	Integrated Product Team
ISSA	International Space Station Alpha
kg	Kilogram
Max	Maximum
micro-g	Micro Gravity
MPLM	Mini Pressurized Logistics Carrier
nmi	nautical miles
OIU	Orbiter Interface Unit
ORU	Orbital Replacement Unit
PRLAs	Payload Retention Latch Assembly
Prop	Propellant
ROEU	Remotely Operated Electrical Umbilical
RSA	Russian Space Agency
TIM	Technical Interchange Meeting
SRCK_LD	Stowage Rack Load Factor
STS_BASE	Upmass capability of Shuttle at 230 nmi rendezvous altitude
STS_RES	Space Station Program Office estimated management reserve for post assembly phase
STWRCK	Stowage Rack
SUM	Summation
ULC	Unpressurized Logistic Carriers
ULC_ATT	Weight of ORU interface attachment hardware
USOS	United States On-orbit Segment

I. Background

The approach discussed in this paper presents the development process and resultant relationships employed in the ISSA Integrated Traffic Model*.

The Traffic Model identifies all vehicles docking to and departing from the ISSA. It characterizes traffic density patterns, upmass requirements for the ISSA, capabilities of cargo vehicles (CV) delivering those requirements, and propellant usage.

The initial development of the Traffic Model capitalized on the Integrated Product Team (IPT) processes put in place at the Johnson Space Center. Continual enhancements to the Traffic Model is streamlined by the very same processes.

This paper will first discuss the development process followed by a detailed discussion of the key relationships that are required to work together to allow a traffic model to be successfully constructed.

The traffic model considers: the Russian Space Agency (RSA) provided Progress-M, Progress-M2 † and Soyuz-TM; the European Space Agency (ESA) provided Automated Transfer Vehicle (ATV) ¥; and, the Space Shuttle as Cargo Vehicle candidates *.

Input data used by the ISSA Traffic Model is still under development. Results shown in this paper should be considered preliminary and subject to change.

The initial tooling of the ISSA planning base for the traffic model by defining their requirements in areas such as logistics, Flight Crew System resupply, and Environmental Control and Life Support System (ECLSS) resupply. Other items which include altitude and propellant strategies provide necessary inputs to the traffic model.

The altitude and propellant requirements like the logistics and maintenance requirements are derived from ISSA subsystem and analysis tools that take into consideration all required technical aspects of the ISSA design. The data these tools provide are the key drivers to the Traffic Model. The altitude and propellant numbers become highly interactive with the maturity of the model development, as vehicle launch dates change so do the rendezvous altitudes and ISSA propellant requirements. The analytical processes and tools used to derive these data are not discussed in this paper.

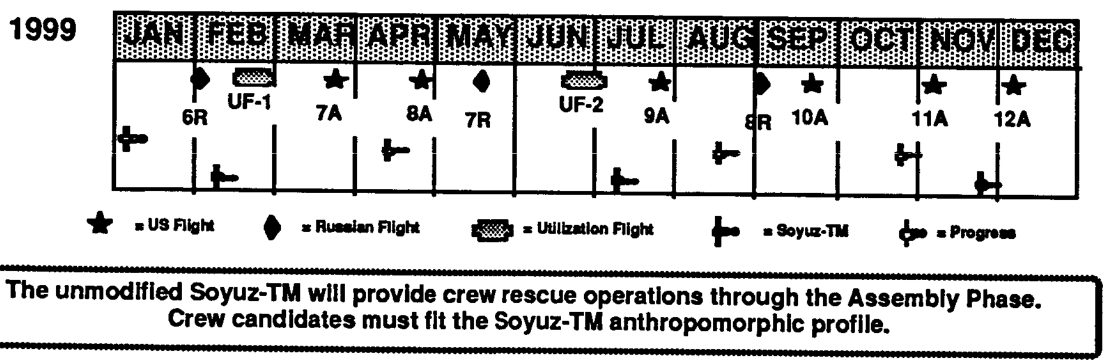

Figure I. 1999 Assembly Year Traffic Density for ISSA

Traffic Model was done on Micro Soft Excel in the Macintosh format •

II. Traffic Model Development

Each IPT, as part of their on-going design work, established the

Figure I shows the assembly phase traffic patterns / density profile for the year 1999#. As can be seen by Figure I traffic to the station is evenly spread throughout the year. February shows the most amount of traffic with a Russian assembly flight

(6R), a US Utilization Flight (UF-1) delivering the first set of science experiments, and a Russian Soyuz flight rotating up to three (3) station crew members††.

RSA data used in the ISSA Traffic Model is derived from Russian technical reports and information documented in protocols from US and RSA Technical Interchange Meetings †.

A primary object of the ISSA Traffic model is to project total station consumable rates. This is required in order to identify loading effects on cargo vehicles and to set up the initial architecture of the model. Loading of any cargo vehicle (CV) is determined by examining the duration of stay on orbit <u>and</u> when the next CV is scheduled to arrive. Consumables are identified as propellant, gases, water, and crew supplies ¶¥

Another primary objective of the traffic model was the ability to maintain a status of cargo vehicle propellant loading over time. A CVs ability to meet ISSA propellant requirements are paramount to the success of the ISSA. In that light the ISSA Traffic Model must maintain a profile of on-board propellant storage of not only the CV but also the ISSA storage tanks plus keeping track of propellant requirements status. This requires keeping track of the total on-board propellant load while continually comparing it to the contingency propellant storage requirements for the ISSA.

The science requirement for micro gravity constitutes the third objective of the traffic model.

The ISSA must be flown such that once fully assembled some selected areas on-board must meet a .2 micro gravity perpendicular component to orbital average quasi-static acceleration vector. This environment must be not be disturbed for at least 180 days per year in no less than 30 day increments. The micro-gravity requirement profiles the docking windows for all vehicles going to and returning from ISSA, opportunities for reboosting the station to maintain its operational orbit, and maintenance periods that would impact the stations micro gravity environment.

A micro gravity mission profile was identified for planning guidelines which allows for eight (8) 30 day micro-g periods per year, refer to Figure II, Concept of Operations and Utilization increment definition profile ¶¥.

<u>II. RSA Key Traffic Model Relationships</u>

Since the ISSA crew members will be using the cargo vehicle as a storage location for the supplies they carry, the loading of water, gases, propellant and crew supplies must be based on how long the vehicle will be attached to the station.

The traffic model considers the use rate of each of the consumables, while the vehicle is attached to the station, in determining the correct CV load factors.

To establish the relationships between the consumables and the loading factors of CVs simple equations have been developed. For these relationships "if/then" expressions are used.

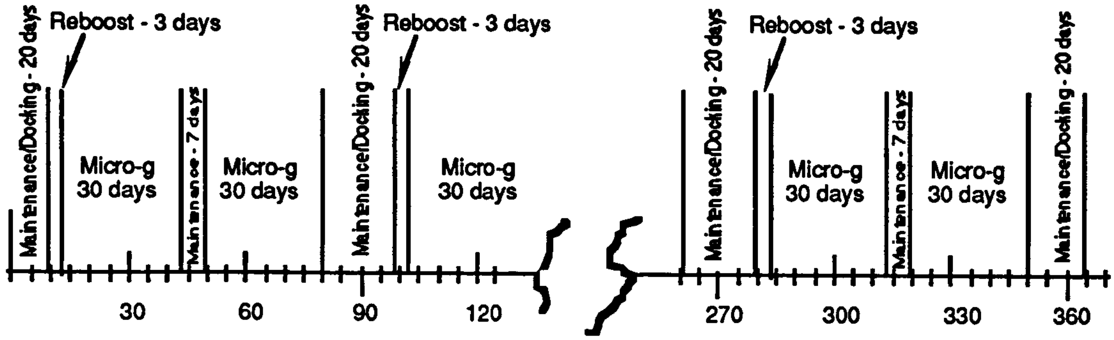

Figure II. Concept of Operations and Principles Micro gravity profile

An "if/then" statement is defined as a calculation or expression that is dependent on a binary condition or conditions. The storage of water considers:

IF(SUM(H_2O) > CV Capability, CV CAP, SUM (H_2O))

Where as: if the sum of the water required during the stay time of the cargo vehicle is greater than the CVs water tanks then the amount of water assigned to that CV is full water tanks. If not, then the amount of water the CV is to carry is the amount required.

The SUM(H_2O) is determined by calculating the consumable rate of water from the date that cargo vehicle docked to the date the next cargo vehicle docks. This expression not only allows a comparison of requirements and cargo vehicle capabilities, but also the ability to assess different cargo vehicles and changes in capacity designs. This same relationship applies to the CVs ability to carry gases (Nitrogen, Oxygen or a combination of both).

In modeling the operational phase of the ISSA the Traffic Model assigns the highest priority to crew supplies, then water and gases, followed by maintenance logistics. Any remaining upmass capability is assigned to transport propellant and then to the Experiments. The optimization of CV loading is currently adjusted manually, but this task is a candidate for automation on future ISSA Traffic Model upgrades.

Propellant loading for the CV is determined by the following expression:

IF (CV Max Cap - (CV Base + (230-docking altitude) * CV Orbit penalties) - SUM (CV Load) > = CV Prop Cap), CV Prop Cap, CV Max Cap - (CV Base + (230-docking altitude) * CV Orbit penalties) - SUM (CV Load))

This expression considers the CV type as a variable, the payload capability of the CV, what has already been loaded, the maximum capacity for propellant, and upmass penalties associated with docking altitudes.

Since the basic load of the CV is calculated from consumption rates and duration on-orbit the massaging of docking and departure dates preserve the necessary loading relationships.

One of the key factors in CV propellant loading is the relationship between propellant available on orbit in both the CV and the station elements to the propellant required during the period the CV will be at the station.

This relationship is continually maintained by first keeping track of the propellant within the Service Module, Storage Tank Module (FGB Module), and the attached cargo vehicle. Then comparing it to on-board propellant requirements at specified events (vehicle docking / departures, reboosts, etc.). The traffic model alerts the user when any event results in a negative propellant margin.

Another aspect of the ISSA Traffic Model is the volumetric loading assessment. An average of 200 kg / Cubic Meter is used for all RSA pressurized cargo [*,†,¥]. When this loading results in exceeding the capability of the CV an indicator alerts the user of the violation.

For the Space Shuttle rack loading coefficients are used that identify total rack weight, carrying load and volume capability.

III. Space Shuttle Key Relationships

The ISSA Traffic Model investigates two (2) types of Space Shuttle mission scenarios.

The first scenario is a dedicated pressurized cargo mission where a 16 rack, 20,000 lbs (9072 kg's) capacity mini pressurized logistics carrier (MPLM) is used. The MPLM is transported to the ISSA in the Space Shuttle payload bay, upon arriving it is removed and attached to a common berthing mechanism where it will remain as the crew removes and replaces cargo.

Scenario number two is a dedicated unpressurized Space Shuttle mission where up to approximately 26,000 lbs (11,794 kg's) of unpressurized cargo is transported on two (2) Unpressurized Logistic Carriers (ULC) to and from the space station. The ULC is structure that can allow multiple and various sized unpressurized elements to be delivered and returned in the payload bay of the Space Shuttle.

Space Shuttle Scenario #1 - Pressurized Cargo Flight:

In the first scenario the traffic model algorithms calculate the capability of the MPLM to carry cargo to the station by the following expression:

(STS_BASE + (230 nmi - docking altitude) * 100 lbs) - STS_RES - EXT_AL - MPLM_ATT - APCU - ROEU - MPLM - 20 * locker_wt - OIU - 2 Shuttle crew)

Where:

STS_BASE	Upmass capability of Shuttle at 230 nmi rendezvous altitude
STS_RES	Space Station Program Office estimated management reserve for post assembly phase
EXT_AL	Weight of external airlock
MPLM_ATT	Weight of MPLM attachment hardware (PRLAs)
APCU	Weight of APCU
ROEU	Weight of ROEU
MPLM	Weight of MPLM
locker_wt	Weight of 20 middeck lockers
OIU	Weight of OIU

The result of this equation is used as a basis for the cargo loading estimates. After assembly of the space station (post assembly phase) the traffic model assumes 40 % of the available upmass is reserved for science and 60% is reserved for crew supplies and space station maintenance logistics.

The space station design teams are interested in tracking the mass and volume of the maintenance Orbital Replacement Units (ORUs) that can be delivered. Therefor the model takes into consideration the average amount of mass and volume that can be placed in a space station stowage rack and deducts the rack weight from the logistics allocation of upmass. This can be seen in the following calculation:

IF (Shuttle upmass capability > 20000, IF((20000 * 0.6 - unpressurized cargo - crew supplies) - ((20000 * 0.6 - unpressurized cargo - crew supplies) / SRCK_LD) * STWRCK < = logistic upmass requirement, (20000 * 0.6 unpressurized cargo - crew supplies) - ((20000 * 0.6 - unpressurized cargo - crew supplies) / SRCK_LD) * STWRCK, logistic upmass requirement), IF((Shuttle upmass capability * 0.6 - unpressurized cargo - crew supplies) - ((Shuttle upmass capability * 0.6 - unpressurized cargo - crew supplies) / SRCK_LD) * STWRCK < = logistic upmass requirement, (Shuttle upmass capability * 0.6 - unpressurized cargo - crew supplies) - ((Shuttle upmass capability * 0.6 - unpressurized cargo - crew supplies) / SRCK_LD) * STWRCK, logistic upmass requirement)))

Where:

SRCK_LD	Average load for a storage rack
STWRCK	Weight of storage rack

The above calculation also takes into consideration the maximum capability of the MPLM and the upmass capability of the Space Shuttle at the assigned docking altitude.

The spacing of Shuttle launches has been driven by the micro-g profile (Figure II) and the Space Station Freedom retained design features.

These design features include the allocation of 40 % of the upmass to science, the number of stowage and refrigeration racks in the Habitation Module and the capacity of the MPLM all contribute to a 90 day crew supply replenishment cycle. Therefore as a basic scheduling template four (4) pressurized Shuttle mission launches are scheduled on 90 day centers. A 5th Shuttle mission, that carries unpressurized cargo, is scheduled within one (1) of the 90 day cycles.

Space Shuttle Scenario #2 - Unpressurized Cargo Flight:

The unpressurized Shuttle mission scenario is handled in the same manner as the pressurized scenario. Volumetric assessments are handled as secondary checks once the loading of each vehicle is determined. The traffic model calculates the Shuttle upmass capability with the following expression:

STS_BASE + (230 nmi - docking altitude) * 100) - STS_RES - ULC * 2 - ULC_ATT*2 - PRLA * 2 - APCU - EXT_AL - 20 * locker_wt - OIU

Where:

STS_BASE	Upmass capability of Shuttle at 230 nmi rendezvous attitude
STS_RES	Space Station Program Office estimated management reserve for post assembly phase
ULC	Base weight of ULC

MF/MC Resupply Assessment - USOS Pressurized Logist upmass (based on: 9/28/94 Assembley Sequence)

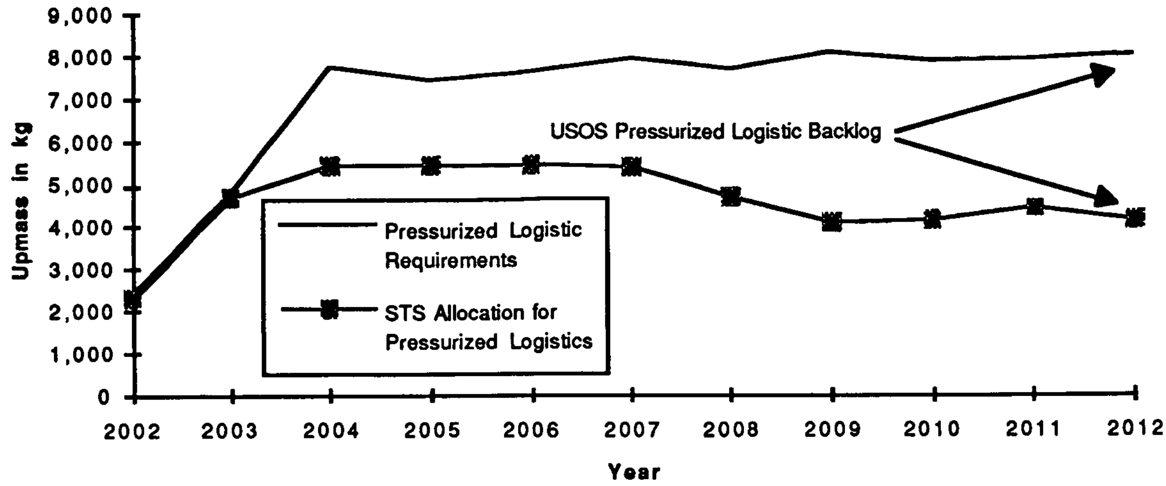

Figure III. USOS Comparison Between Pressurized Logistics requirements and Resupply Capabilities

ULC_ATT	Weight of ORU interface attachment hardware
PRLA	Weight of ULC attachment hardware
EXT_AL	Weight of external airlock
APCU	Weight of APCU
locker_wt	Weight of 20 middeck lockers
OIU	Weight of OIU

For the Unpressurized Shuttle flight load capability the traffic model uses the following expression:

IF (Science unpressurized upmass + Logistic Maintenance requirements > Shuttle upmass capability , Shuttle upmass capability, Science unpressurized upmass + Logistic Maintenance requirements)

IV. Traffic Model Results

Several outputs of the traffic model are used by the ISSA Program.

The docking and undocking of the visiting vehicles set the basis for determining quiet zones from which micro gravity periods can be planned.

The annual summaries provide comparisons of requirements versus capabilities for both the United States On-orbit Segment (USOS) and the Russian Segment. At the time of this paper the ISSA Traffic Model indicates a backlog of USOS pressurized logistics (refer to Figure III).

The annual average mass of cargo delivered to the station is approximately 100 metric tons per year (includes carrier weights). 20 to 25 metric tons are delivered to the Russian Segment ¶ and is comprised of approximately eight (8) to 11 metric tons of propellant, 6800 kg of crew supplies, 3.3 metric tons of experiment hardware, 2-3 metric tons of water, two (2) metric tons of maintenance logistics, and 500 kg of gases. The USOS annual average mass is approximately 75 to 80 metric tons and is comprised of 18 to 23 metric tons of science, 8 metric tons of crew supplies, 8 to 12 metric tons of maintenance logistics, and 37 metric tons of Flight Support Equipment (FSE).

V. Summary

All the crew rotation logistics, propellant, and other supply requirements have been aggregates as the basis for defining a traffic model to the ISSA.

Numerous expressions have been developed which allow definition of the various consumption rates and their relationship to each other. This has all been integrated in commercial off the shelf (COTS) software and has set up base rules for enhanced modeling through higher order expressions. Rapid prototyping of certain key design characteristics of cargo vehicles and ISSA capabilities allow for in-depth design assessments in a rapid changing design environment.

Reference Documents:

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(#)HS-DF-AT-1-ESA Automated Transfer Vehicle Design Reference Missions Document, October 1994.

(¶)SSP 50011 VOL-1 Concept of Operation and Utilization ISSA Volume I, November 1994.

(¶)SSP 50011 VOL-2 Concept of Operation and Utilization ISSA Volume II, November 1994.

(¶)SSP 50011 VOL-3 Concept of Operation and Utilization ISSA Volume III, November 1994.

(¥)SSP 4100, System Specification for the International Space Station Alpha, February, 1994.

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PREDICTIVE ENGINEERING IMPLEMENTATION AT KSC

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Abstract

This paper provides an overview of what the primary contractors at Kennedy Space Center (KSC) are doing in the field of predictive engineering. The technologies employed by each of the contractors and the cost savings associated with the implementation of these predictive engineering methods are discussed. The sources include predictive engineering implementation plans, published by each of the contractors and interviews with the authors of these implementation plans.

Introduction

The primary mission of Kennedy Space Center is to launch Space Shuttles. Shuttle launch costs are comprised of manpower, material, and equipment. There are billions of dollars invested in equipment located on the Kennedy Space Center which is essential to launching Shuttles. This equipment must be in a safe and operable condition upon demand.

However, electrical and mechanical equipment will gradually deteriorate over time and this will eventually cause the equipment to fail. The harsh environment that is present at KSC due to the high humidity, salt air and hazardous chemicals increases the number of equipment problems. Preventive maintenance is used to slow this deterioration and thereby extend the useful life of the equipment. Traditional preventive maintenance provides for planned shutdowns during periods of inactivity or low usage for major overhauls.

Predictive engineering, a branch of preventive maintenance, is a method to systematically monitor equipment and perform operational trend analysis on a regularly scheduled basis to determine the condition of the equipment. On-line detection, trending and diagnostics provide an early warning of potential equipment failure and reduce the need for traditional preventive maintenance. Predictive engineering also decreases unexpected breakdowns and helps to ensure the continuity of operation.

A preventive maintenance program which utilizes predictive engineering methods provides numerous benefits including:

Reduced maintenance downtime
Reduced unplanned failures
Reduced risk of induced failures
Reduced repair costs
Reduced manpower requirements
Increased equipment availability
Extended useful life of equipment
Improved safety and reliability

In the current environment of decreased funding there is a constant demand to reduce cost in all areas. The cost of preventive maintenance is no exception. The implementation of predictive engineering into the existing Kennedy Space Center preventive maintenance programs has resulted in significant cost savings.

Shuttle Processing Contractor

The Shuttle Processing Contractor (SPC) introduced predictive engineering in 1988 with Vibration Trend Analysis to address high failure rates of the Orbiter Processing Facility (OPF) Environmental Control System (ECS) Ground Support Equipment. The initial program of Vibration Trend Analysis involved 66 ECS machines from Launch Pads A and B, the OPF's, and the Portable Purge Units for which the prime contractor has maintenance responsibility. SPC has stated that this program effectively reduced the failure rate of ECS rotating equipment and the risk of flight hardware damage and personnel injury.

In 1990 a plan to continue the Vibration Trend Analysis program and expand predictive engineering was developed. This plan has been applied to all mechanical and electrical Ground Support Equipment, Facility Equipment, and to some designated flight hardware. In order to accomplish this the Kennedy Space Center Integrated Schedule, which drives monitoring and data collection schedules, had to be revised.

There are currently three people under the Shuttle Processing Contract that support over 1100 items being monitored by predictive engineering methods. These technologies now include Vibration Trend Analysis, Ferrography Trend Analysis, Thermography, Ultrasonics, Ultrasound, Laser Alignment, Laser Shearography, and Motor Circuit Analysis.

Vibration Trend Analysis evaluates the on-line condition of mechanical components and their effect on related pieces of mechanical hardware. It can detect, identify and isolate specific component degradation in bearings, gears, pulleys, blowers, fans, belts, and couplings. For this kind of analysis, the type and amount of data required will vary from one analysis problem to another. Fortunately, given the advances in microprocessors and vibration instrumentation, vibration analysis is an adaptive process where real time changes to test frequencies and directions can be made in order to provide more information.

Ferrography Trend Analysis is analogous to a common blood test. This analysis uses diagnostic and predictive techniques to evaluate the on-line condition of interacting lubricated or fluid powered parts. The lubricants or fluids are analyzed for condition, level, and type of contamination. Analysis of wear particles can isolate a failing component, the mode of failure, and the estimated time to failure through trending. Equipment life is extended by oil analysis instead of depending entirely on operating hours as the driver for scheduled maintenance. This technology identified three suppliers who inadvertently shipped oil that was contaminated with sand and metal particles. As a result, a nationwide alert was issued and potential damage to the KSC elevator and crane systems was avoided.

Thermography is the science of detecting temperature differences by scanning infrared emissions. It is used to analyze equipment that exhibits thermal discrepancies prior to failure or when not operating properly. This includes equipment as varied as electrical panels, circuit boards, pumps, motors and many others. There are several advantages to using non-contact thermal infrared measurement as opposed to more conventional methods of temperature measurement. The most commonly stated advantages are that it is non-intrusive, it is much quicker, and it can measure the temperature at the surface of the equipment. The infrared camera effectively detected a defective fuse at one of the KSC electrical switchyards. If conventional preventive maintenance methods had been used instead, the arcing would have gone undetected. This would have caused emergency power to be activated and could have resulted in a possible launch delay.

Ultrasonics technology detects hidden flaws in materials, especially metals. It also verifies weld joints and fluid levels by monitoring the high frequency sound generated by the turbulent or restricted flow of escaping gasses. This technology has advanced into a completely digital and portable microprocessor controlled ultrasonic flaw detector. It is safer and faster than current X-ray technology.

Ultrasound is an acoustical detection system that detects sound waves generated by a component and transmitted through some type of medium. This medium can be air, water, or organic or inorganic material. It is a technology which primarily detects leaks involving all types of fluids. Equipment such as gearboxes, compressors, relief valves, boilers, and tube banks can be easily inspected using ultrasound.

Laser Alignment is the newest predictive engineering method to be employed in the alignment of rotating systems. It detects misalignment in mechanical equipment, which places undue force on bearings, and can lead to accelerated wear or possible catastrophic failure. It verifies proper installation and even fabrication of mechanical systems prior to operation. It also monitors proper alignment during equipment operation. Correct alignment has been credited with saving as much as ten percent on power consumption.

Laser Shearography is a form of nondestructive testing for general purpose strain analysis and inspection of metallic or composite materials. It is particularly useful for detecting corrosion, which can go unnoticed during a typical visual inspection. Laser Shearography has many applications at KSC, principally in detecting debonding of composite structures on the Orbiter, the External Tank, and the Solid Rocket Boosters.

Motor Circuit Analysis determines the level of degradation in electrical motor circuits such as individual phase resistance from the power bus disconnect through the motor windings, phase to ground resistance, inductance of the motor coils and capacitance of each of the three phases to ground. Detecting and correcting a 4.5% phase imbalance saves 25% in additional power consumption and can double the useful life of the motor. Considering that SPC engineers believe that most of the three phase motors in operation today are out of balance, this is one area where enormous cost savings are anticipated at KSC.

Through the use of these eight preventive engineering methods the contractor was able to save approximately two million dollars last year alone. Some of these technologies have exhibited very high cost paybacks. The Shuttle Processing Contractor believes that this type of program has and will continue to save lives, extend the useful life of equipment, and increase equipment availability in order to insure operational success.

Payload Ground Operations Contractor

The Payload Ground Operations Contractor (PGOC) began incorporating predictive engineering methods into their preventive maintenance program with the use of Vibration Analysis in 1988 and Ferrography in 1989. In 1992 they began focusing on a reliability centered maintenance program. Systems engineers reviewed the list of equipment Preventive Maintenance Instructions (PMI) and provided suggestions as to what requirements were needed in order to utilize predictive engineering technologies which would result in a more efficient and reliable approach to maintenance. They then rewrote selected PMI's and added documentation to incorporate Vibration Analysis, Thermography, Ferrography, Ultrasonic Monitoring, and Laser Alignment.

The Payload Ground Operations Contractor has now established a complete reliability centered maintenance plan which combines predictive technologies with preventive maintenance procedures. Five basic questions are addressed to determine the amount of maintenance required for each piece of equipment:

1. What does the equipment do?
2. What failures occur?
3. What are the consequences of the failures?
4. How can the failures be prevented?
5. What is the cost benefit of maintenance versus failure.

In addition, criteria for predictive maintenance depends on the type of equipment, how it is used, and the mission criticality or safety aspects of that use. Identical pieces of equipment can have dissimilar maintenance requirements in different applications. As a result of this, four distinct levels of maintenance were identified.

The Level I maintenance procedure is for equipment that requires no maintenance. The hardware is run to failure and then repaired. The reason for this is that the cost of replacing or repairing the equipment is less than the cost of maintenance. It should also be noted that this level of maintenance only applies to non-critical systems where consequences of failure do not impact safety.

The Level II maintenance procedure specifies that only the maintenance which is required by KSC regulations will be performed. In some cases, since this is still non-critical equipment, a waiver to the regulations will be processed to reduce the amount of maintenance that must be done. Equipment within this category may require some predictive maintenance, but it is usually hardware that can be shut down for extended periods of time for repair or preventive maintenance.

Equipment that falls under the Level III maintenance category are items where the amount of preventive maintenance has been reduced and predictive technologies are being utilized to monitor and trend any potential problems.

The Level IV category is for those items that require full maintenance, both preventive and predictive, to avert functional failures. These are critical items, where a single failure could result in the loss of life or damage to flight hardware. Hardware is also designated Level IV if it monitors hazardous operations and where safety is a major concern.

As noted earlier, the PGOC has focused on rewriting the PMI's to incorporate predictive engineering technologies into these documents and as a result they measure their cost savings in terms of man-hours. In fiscal year 1994 alone, they saved approximately 12,000 man-hours through the implementation of predictive maintenance methods in place of traditional preventive maintenance. A large portion of these savings came from changing the PMI's for the Heating, Ventilation, and Air Conditioning units, which include all facility boilers and pumps, along with the compressed air and vacuum systems.

This has been accomplished with a staff of two engineers who perform predictive analysis and trending on 185 pieces of equipment. The amount of equipment tested using predictive technologies is anticipated to increase during the next year with the addition of the Space Station Ground Support Equipment and facility hardware.

Base Operations Contractor

The Base Operations Contractor (BOC) maintenance program is a reliability centered maintenance philosophy that incorporates preventive, predictive, and proactive maintenance with equipment life cycle management. This results in minimizing equipment failures that could impact critical KSC systems and accomplishment of required maintenance in the most cost effective manner. The BOC uses predictive engineering as a means to complement their preventive maintenance program.

Their approach to predictive engineering is similar to that of the payloads contractor. They do not attempt to apply predictive engineering methods to all their systems. When the predictive engineering plan was first established, all of the equipment was assessed based on operational criticality. The following parameters determine these criticalities:

Safety
Mission
Environmental
Cost of Maintenance/Replacement

The Base Operations Contractor is responsible for 32,000 pieces of equipment. They currently monitor 51% of the two thousand pieces of equipment that have been targeted for predictive analysis. This has been accomplished with a staff of two engineers. They have also developed a detailed data base to keep track of equipment, failures, and savings associated with the implementation of the predictive engineering methods.

In addition to the technologies discussed previously, the BOC also utilizes several different predictive maintenance methods, including Megger Testing, Power Factor Testing, Breaker Timing Testing, Contact Resistance, Insulation Oil Analysis, Gas-In-Oil Analysis, Impedance Testing, and Hi-Pot Testing.

Megger Testing is primarily used on transformers, circuit breakers, and switch gears. This is a direct current test where a voltage is applied to the equipment in order to determine insulation resistance and monitor trends.

Power Factor Testing is basically a power loss measurement. It is a non-destructive alternating current test that shows the condition of the insulation. When the circuit impedance changes due to aging, moisture, contamination, insulation shorts, or damage, the power factor will increase. The BOC engineers believe that this is one of the most useful predictive engineering tests for transformers, circuit breakers, and switch gears.

Breaker Timing Testing is a mechanical test which displays the speed and position of breaker contacts before, during , and after an operation. It is used to trend information on medium or high voltage breakers in order to determine if adjustments need to be made to the breaker operating mechanism.

Oil Analysis is used on high voltage transformers, circuit breakers and medium voltage switches where oil is supplied as an insulator. Performing this analysis on the electrical insulating oil provides a great deal of information about the operational history and current condition of the equipment. Any type of heating, arcing, or coagulation produces by-products that can be detected in the insulation oil.

Gas-In-Oil Analysis is one of the best predictive engineering tests for transformers that use oil insulation according to BOC engineers. By analyzing a small sample of oil to determine what gases are present, failure and degradation patterns internal to the transformer are be identified. This predictive engineering technology was successfully identified acetylene in the insulation oil in one of the substations. Since acetylene is normally not present unless there has been arcing, a critical problem was recognized and corrected prior to failure.

Impedance Testing is used to trend the internal impedance of battery cells. Since this impedance is directly related to the remaining capacity of the battery, it projects battery end-of-life or cell degradation.

Hi-Pot Testing is a technology used primarily on cables and switches. It is a direct current, high voltage test that detects excessive leakage current. It is used for testing new equipment and also to trend the degradation of equipment in use. However, Hi-Pot has the potential be a destructive test, so it is not a common predictive maintenance tool. In many cases Power Factor Testing replaces Hi-Pot Testing for high voltage cables. Hi-Pot Testing is then used only when the insulation condition has reached a questionable threshold.

Through the use of these predictive engineering technologies the Base Operations Contractor has realized almost one million dollars in cost savings over the past two years. The investment in the predictive maintenance program thus far has been minimal. Approximately $450K has been spent on equipment and salaries. The BOC anticipates that this program will save ten million dollars within the next ten years.

Conclusion

It is evident that there are numerous predictive technologies that indicate machine health and provide critical information about the operational condition of equipment. Through effective utilization of these predictive engineering methods, the amount of preventive maintenance required to support critical systems has been reduced, resulting in considerable manpower savings. The implementation of predictive engineering technologies also provides an early indication of potential problems. Therefore, significant cost savings have been and will continue to be achieved through the reduction of downtime due to failures and scheduled maintenance, and extended hardware life. In addition to the long term cost savings, an increase in the overall reliability of the systems at KSC will continue to be realized.

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Lockheed Predictive Engineering Technology Program Implementation Plan, Grady McCorquodale

EG&G Predictive Maintenance Plan, A. M. Rose and A. K. Dowell

P/PM Presentation, A. M. Rose

PGOC Predictive Maintenance Program Presentation, Ron Gawlik

Reliability Centered Maintenance Report, Ron Gawlik

Predictive Maintenance Requirements & Specifications, Ron Gawlik

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INTEGRATED LOGISTICS SUPPORT ANALYSIS OF THE INTERNATIONAL SPACE STATION ALPHA

AN OVERVIEW OF THE MAINTENANCE TIME DEPENDENT PARAMETER PREDICTION METHODS ENHANCEMENT

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Abstract

The objective of this publication is to introduce the enhancement methods for the overall reliability and maintainability methods of assessment on the International Space Station. It is essential that the process to predict the values of the maintenance time dependent variable parameters such as MTBF over time do not in themselves generate uncontrolled deviation in the results of the ILS analysis such as Life Cycle Cost, spares calculation, etc. Furthermore, the very acute problems of micrometeorite, Cosmic rays, flares, atomic oxygen, ionization effects, orbital plumes and all the other factors that differentiate maintainable space operations from non maintainable space operations and/or ground operations must be accounted for. Therefore, these parameters need be subjected to a special and complex process. Since reliability and maintainability strongly depends on the operating conditions that are encountered during the entire life of the International Space Station, it is important that such conditions are accurately identified at the beginning of the Logistics Support requirements process. Environmental conditions which exert a strong influence on International Space Station will be discussed in this report. Concurrent (combined) space environments may be more detrimental to the reliability and maintainability of the International Space Station than the effects of a single environment. In characterizing the logistics support requirements process, the developed design/test criteria must consider both the single and/or combined environments in anticipation of providing hardware capability to withstand the hazards of the International Space Station profile. The effects of the combined environments (typical) in a matrix relationship on the International Space Station will be shown. The combinations of the environments where the total effect is more damaging than the cumulative effects of the environments acting singly, may include a combination such as temperature, humidity, altitude, shock, and vibration while an item is being transported. The item's acceptance to its end-of-life sequence must be examined for these effects.

1. REFERENCES

A. Space station freedom external maintenance task team, July 1990, final report; and

B. External maintenance solution team, January 1991, final report.

2. OBJECTIVE

2.1 The objective of this report is to note the environmental factors in a space environment which must be accounted for in order to accurately forecast the maintenance time dependent variables (e.g: MTBF).

3. INTRODUCTION

3.1 In response to Reference A task, a series of three (3) reports which describe the initial approach to conduct refinement processes for the maintenance time dependent parameters such as MTBF in order to accurately forecast the Logistics Support requirements were completed. This report is the first of the three reports. The paramount and complex problem relative to the time dependent maintenance variable parameters became apparent as a result of the investigations performed on the RAM packages.

3.2 The process to predict the values of the maintenance time dependent variable parameters such as MTBF over time, as report 1 and annex A of report 2 (this report is labelled as: "INTEGRATED LOGISTICS SUPPORT ANALYSIS OF THE INTERNATIONAL SPACE STATION, BACKGROUND AND SUMMARY OF MATHEMATICAL MODELLING & FAILURE DENSITY DISTRIBUTIONS PERTAINING TO MAINTENANCE TIME DEPENDENT PARAMETERS", and is published in this symposium) elucidate, must be treated by a complex process to prevent uncontrolled deviation in the results of the ILS analysis such as Life Cycle Cost, spares calculation, etc. Furthermore, the very acute problems of micrometeorites, Cosmic rays, flares, atomic oxygen, ionization effects, orbital plumes and all the other factors that differentiate maintainable space operations from non maintainable space operations and/or ground operations need to be accounted for. Therefore, these parameters need be subjected to a special and complex process.

4. ENVIRONMENTAL FACTORS

4.1 Since reliability and maintainability strongly depends on the operating conditions that are encountered during the entire life of the MSS, it is important that such conditions are accurately identified at the beginning of the Logistics Support requirements process. Environmental conditions which exert a strong influence on MSS are included in table 4.1 which provides a typical checklist for space environmental coverage. Concurrent (combined) space environments may be more detrimental to the reliability and maintainability of the MSS than the effects of a single environment. In characterizing the logistics support requirements process, the developed design/test criteria must consider both the single and/or combined environments in anticipation of providing hardware capability to withstand the hazards of the MSS profile. Figure 4.1 illustrates the effects of combined environments (typical) in a matrix relationship. It shows the combinations where the total effect is more damaging than the cumulative effects of the environments acting singly, may include a combination such as temperature, humidity, altitude, shock, and vibration while an item is being transported. The items's acceptance to its end-of-life sequence must be examined for these effects. Table 4.2 illustrates the environmental effects on the MSS.

TABLE 4.1: ENVIRONMENTAL COVERAGE CHECKLIST (TYPICAL)

NATURAL	INDUCED
Geomagnetism	Radiation, Electromagnetic
Gravity, low	Radiation, Nuclear
Ionized Gases	Shock
Meteorites	Temperature, High, Aero. Heating
Pressure, Low	Temperature, Low, Aero. Cooling
Pressure, High	Vibration, Mechanical
Radiation, Cosmic, Solar	Vibration, Acoustic
Radiation, Electromagnetic	
Temperature, High	
Temperature, Low	

FIGURE 4.1: EFFECT OF COMBINED ENVIRONMENTS

	Gravity, Low	Ionized gases	Meteorites	Pressure, Low	Radiation, Cosmic	Radiation, Electromagnetic	Radiation, Van Allen
Gravity, Low							
Ionized gases	4						
Meteorites							
Pressure, Low	4	3					
Radiation, Cosmic	7	1		3			
Radiation, Electromagnetic	7	1		3			
Radiation, Van Allen	4						

1 Combine to intensify mechanical deterioration
3 Interdependent (one environment dependent on the other)
4 Coexist with no significant combined effect
7 Unknown (unlikely combination or indeterminate combined effect)
Blank Combination requires further research

TABLE 4.2 ENVIRONMENT EFFECTS

ENVIRONMENT	PRINCIPAL EFFECTS	TYPICAL FAILURES INDUCED
High speed particles (Nuclear Irradiation)	Heating Transmutation and Ionization	Thermal Aging; Oxidation Alteration of chemical, Physical, and electrical properties: Production of gases and secondary particles.
Zero gravity	Mechanical stress Absence of convection cooling	Interruption of gravity dependent functions, Aggravation of high temperature effects.
Ozone	Chemical reactions: Crazing, cracking Embrittlement Granulation Reduced dielectric strength of air	Rapid oxidation; Alteration of electrical properties; Loss of mechanical strength; Interference with function; Insulation breakdown and arc over.
Dissociated gases	Chemical reaction: Contamination Reduced dielectric strength	Alteration of physical and electrical properties; Insulation breakdown and arc over.
Vibration	Mechanical stress Fatigue	Loss of mechanical strength; Interference with function; Increased wear; Structural collapse.

Magnetic field	Induced magnetization	Interference with function; Alteration of electrical properties; Induced heating.
Solar radiation	Actinic and physiochemical reactions; Embritlement	Surface deterioration; Alteration of electrical properties; Discoloration of materials; Ozone formation.

4.3 Low temperatures experienced by the electronic equipment can also cause reliability and maintainability problems. These problems are usually associated with mechanical elements of the system. They include mechanical stresses produced by differences in the coefficients of expansion (contraction) of metallic and nonmetallic materials, embrittlement of non metallic components, mechanical forces caused by freezing of entrapped moisture, stiffening of liquid constituents, etc. Typical examples include cracking of seams, binding of mechanical linkages, and excessive viscosity of lubricants.

4.4 Additional stresses are produced when electronic equipment is exposed to sudden changes of temperature or rapidly changing temperature cycling conditions. These conditions generate large internal mechanical stresses in structural elements, particularly when dissimilar materials are involved. Effects of the thermal shock induced stresses include cracking of seams, delamination, loss of hermiticity, leakage of fill gases, separation of encapsulating components from components and enclosure surface leading to the creation of voids, and distortion of support members.

4.5 Electronic equipment is often expected to be subject to environmental shock and vibration both during normal use and testing. Such environments can cause physical damage to parts and structural members when deflections produced cause mechanical stresses which exceed the allowable working stress of the constituent parts.

4.6 The natural frequencies of items comprising the MSS are important parameters which must be considered in the logistics support of the MSS since a resonant condition can be produced if a natural frequency is within the vibration frequency range. The resonance condition will greatly amplify the deflection of the subsystem and may increase stresses beyond the safe limit.

4.7 The vibration environment can be particularly severe for electrical connectors on the MSS, since it may cause relative motion between members of the connector. This motion, in combination with other environmental stresses, can produce fret corrosion. This generates wear debris and cause large variations in contact resistance.

4.8 High energy radiation can also cause ionization effects which degrade the insulation levels of dielectric materials. The environmental factors that will be experienced by the MSS in its total life cycle requires consideration in the logistics support requirement process. This assures that adequate provisions are made for effective MSS logistic support requirements.

4.9 In the environmental stress identification process that precedes the selection of environmental strength techniques, it is essential that stresses associated with all life intervals of the MSS be considered. This includes not only the operational and maintenance environments, but also the pre operational environments, when stresses imposed on the parts during the manufacturing assembly, inspection, testing, shipping, and installation may have significant impact on the eventual availability of the MSS. Stresses imposed during the pre operational phase are often overlooked. They may, however, represent a particularly harsh environment which MSS must withstand. Often, the environments to which MSS is exposed during shipping and installation are more severe than those MSS will encounter under normal operating conditions. It is also probable that some of the environmental strength features that are contained in the MSS system design pertain to conditions that are encountered in the pre operational phase, and not in conditions that the equipment experiences after being put into its orbit (i.e. infant mortality and/or latent failures).

4.10 Reference A and B indicate that some of the requirements such as the provisions for oxidation, etc have been accounted for as part of the K factors. Our analysis of the K factors, the program's RAM data packages as well as Ref. A and B of indicate the opposite. The failure rates need to be predicted by following a consistent approach which will account for all factors existent in a space environment.

4.11 This consistent approach should include but not be limited to the following:

A. Utilization of constant failure rates (i.e. as report 2 indicate, different family of ORUs belong to different failure distribution). To universally calculate the failure rates using exponential failure distribution is an incorrect method for predicting time dependent maintenance parameters;

B. Ref. B assigns weibull distribution for the life limit items, lognormal for MTTR calculation and exponential for the random failures. This assignment is not accurate and such assignments should be substantiated (please refer to report 2);

C. Ref. A and B take the increase of the failure rate due to duty cycle granted. This is not true due to the fact that items such as battery of a car need be used in order to avoid built up of the chemicals at the contacts interface;

D. NPRD has been used as a basis for comparison for estimating the failure rates. This similiarization at the CDR level is perceived as rudimentary due to the absence of any lay out in the NPRD thereby incurring tremendous inaccuracy for the results;

E. The K factors used by reference A and B does not include the preventive maintenance, inspection and accurate overhead cost. Furthermore, MSS is the first maintainable space operation of its kind and utilization of engineering judgement to determine K factors for this maintainable space operation is not valid. Utilization of previous spacecraft anomalies, as supportive data, is encouraged in parallel with accurate stochastical and analytical techniques which incorporate all the different space environments such as cosmic rays, flares, micrometeorites, etc;

F. In addition, the following areas need to be accounted for:

a. Common mode failures;
b. Common cause failures;
c. Maintenance/Operations induced failures;
d. Life limited items;
e. Duty cycle (i.e. duty cycle does not necessarily increase failure rates);
f. Construction induced failures;
g. micrometeorites, atomic oxygen, flares, cosmic rays;
h. Advances in technology; and
i. Etc.

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The International Space Station Alpha (ISSA) End-to-End On-Orbit Maintenance Process Flow

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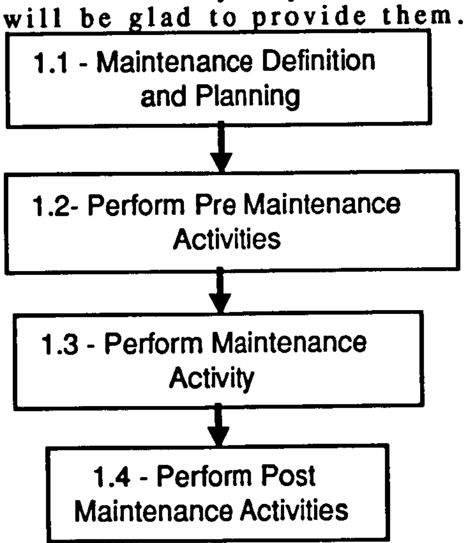
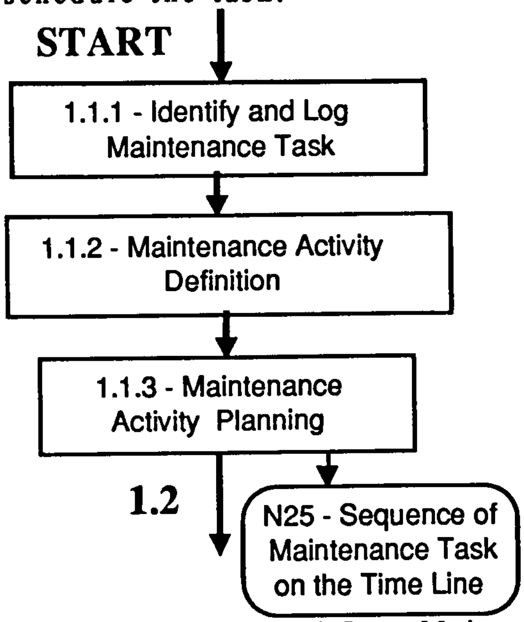
As a tool for construction and refinement of the on-orbit maintenance system to sustain the ISSA, the Mission Operations Directorate (MOD) developed an end-to-end on-orbit maintenance process flow. This paper discusses and demonstrates that process flow. This tool is being used by MOD to identify areas which require further work in preparation for MOD's role in the conduct of on-orbit maintenance operations.

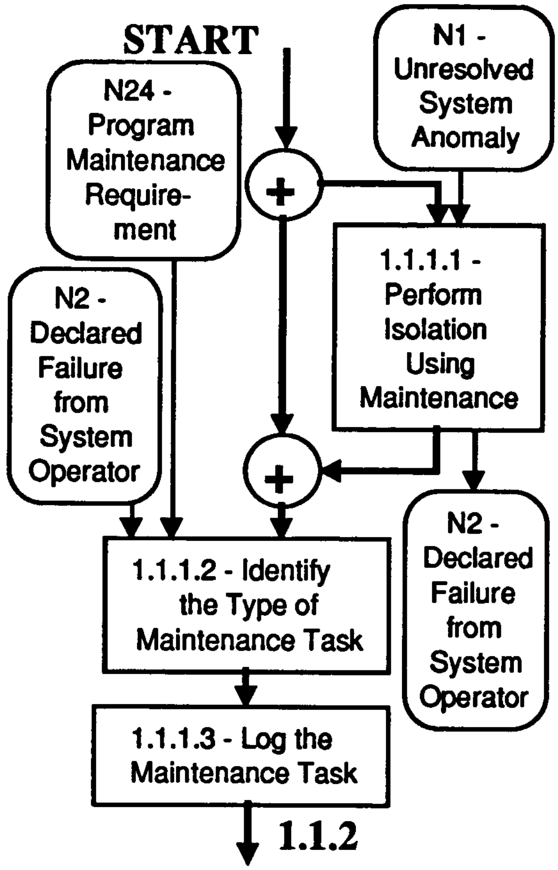
To fit this paper to the page length limitations much of the detail of 1.2 - Perform Pre Maintenance Activities, 1.3 - Perform Maintenance Activity, 1.4 - Perform Post Maintenance Activities, and the Input and Output definitions (N1 to N32) have been eliminated. The process associated with 1.1 - Maintenance Definition and Planning is of greater interest and of most importance to the success of on-orbit maintenance operations. If the details of the latter part of the paper are desired by any reader the author will be glad to provide them.



1.1 - Maintenance Definition and Planning: This process is the tactical method that takes the declared failed item to the stage where the resources are available to do the task and task execution is imminent. Sub processes are:
-Determine which type of maintenance task is appropriate (IVA, EVA, EVR, etc..) (Corrective, Preventive, etc..)
-Ensure that a basic maintenance procedure exists.
-Assure that the resources to perform the task are available on-orbit (including approved procedures, spares, crew time, tools, etc..)
-Determine where this task falls in the backlog and work to evaluate and schedule the task.



1.1.1 - Identify and Log Maintenance Task: Formal statement that a system component is failed. The component may be an Orbital Replacement Unit (ORU), structure, cable, fluid line, etc. Determine if the hardware is IVA, EVA, NASA, NASDA, RSA, ESA, or CSA. Identify the most efficient method of repair EVR or EVA if the task is external to the vehicle. The anomaly report is updated.
1.1.1.1 - Perform Isolation Using Maintenance: Hardware failure isolation that cannot be performed by BITE/BIT, malfunctions, telemetry, or other hands-off type methods may be performed by the crew using isolation/troubleshooting procedures/ methods developed by ground controllers.

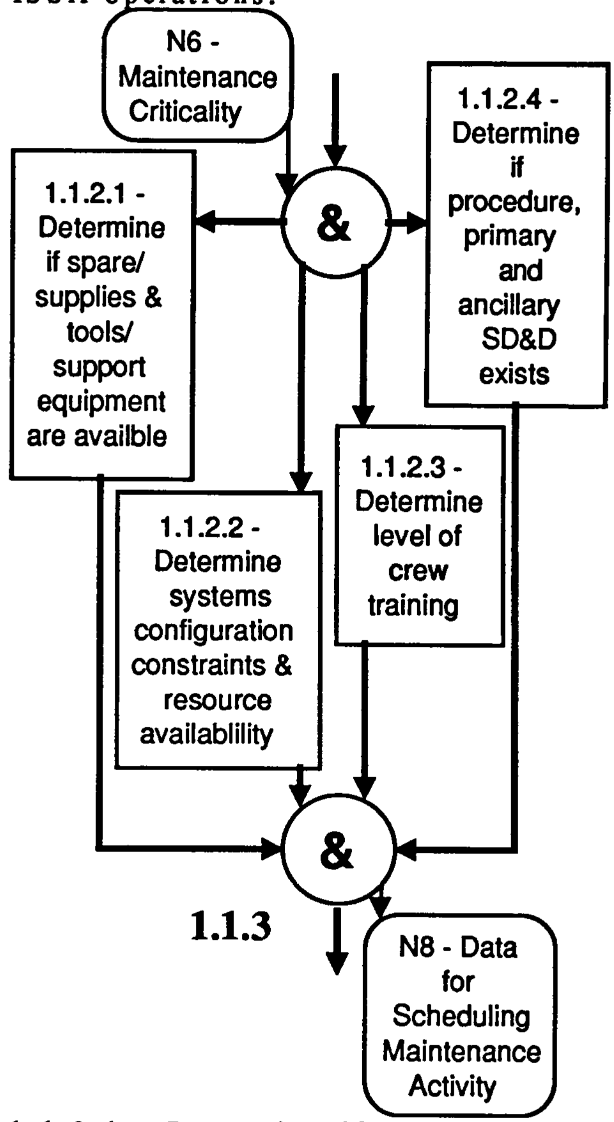


1.1.1.2 - Identify the Type of Maintenance Task: The level of maintenance starts out at Organizational but may progress to Intermediate level if the complete ORU is not stored On-Orbit. The anomaly report is updated.

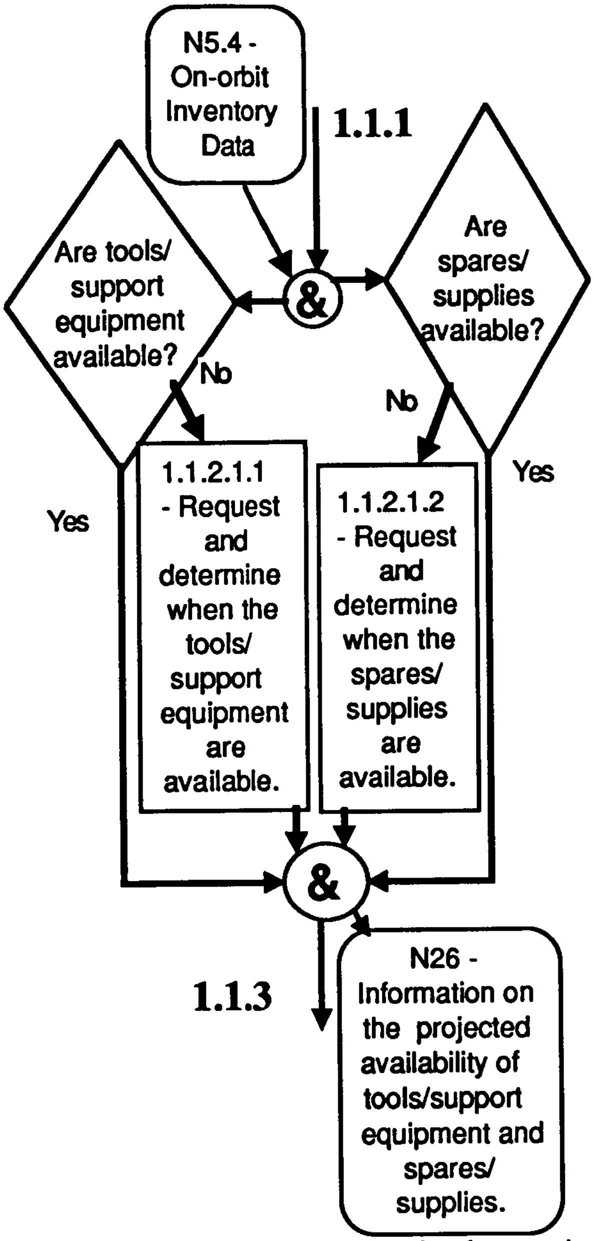
1.1.1.3 - Log the Maintenance Task: After the type of maintenance has been identified the task is logged in so an execution time can be determined though the planning system and then the anomaly report is updated.

1.1.2 - Maintenance Activity Definition: The OSO compiles and submits the data required for scheduling the Maintenance Procedure to the Operations Planning Officer (Ops Planner) so it can be time-lined on the Crew's activity plan. Data includes: activity duration; applicable procedures; Crew and vehicle requirements; Vehicle/system constraints; and any down-link/up-link audio, video, or data requirements.

The Ops Planner uses this information to integrate the maintenance procedure into the crew's activity plan. This information will be available to the entire flight control team so they can assess maintenance activity impacts on ISSA operations.



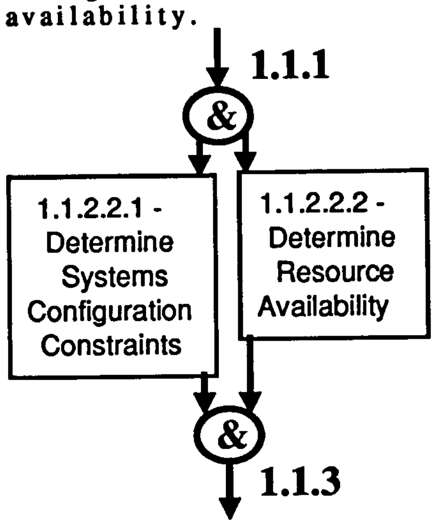
1.1.2.1 - Determine if spare/supplies & tools/support equipment are available: This process involves how maintenance operator interfaces with the program office to obtain maintenance spares/supplies and tools/support equipment. This process also establishes the interface between the maintenance operator and the inventory operator for launch and landing manifesting of items required for maintenance.



1.1.2.1.1 - Request and determine when the tools/support equipment are available: The maintenance operator contacts the inventory operator to determine if the tools/support equipment are available on-orbit. If the tools/support equipment are not available on-orbit, the maintenance operator requests tools/support equipment from the supply support IPT/support equipment IPT. The maintenance operator makes a manifest request to the inventory operator via CMILP. If the spares /supplies, and tools/support equipment are available then the pre-maintenance activities will be performed.

The International Partners (IP) are an exception to this maintenance process flow in that they have analogous organizations to make spares/supplies and tools/support equipment available and they are solely responsible for the maintenance performed on their own hardware.

1.1.2.2 - Determine systems configuration constraints & resource availability.



1.1.2.2.1 - Determine Systems Configuration Constraints: The maintenance operator informs the systems operators of the time to perform the maintenance to determine if the hardware can be down for that period of time and coordinates the systems configuration to perform maintenance

1.1.2.2.2 - Determine Resource Availability: The maintenance operator informs the operations planners the resources required to do the maintenance and confers with systems operators & the operations planners on the impact of performing maintenance on resource availability.

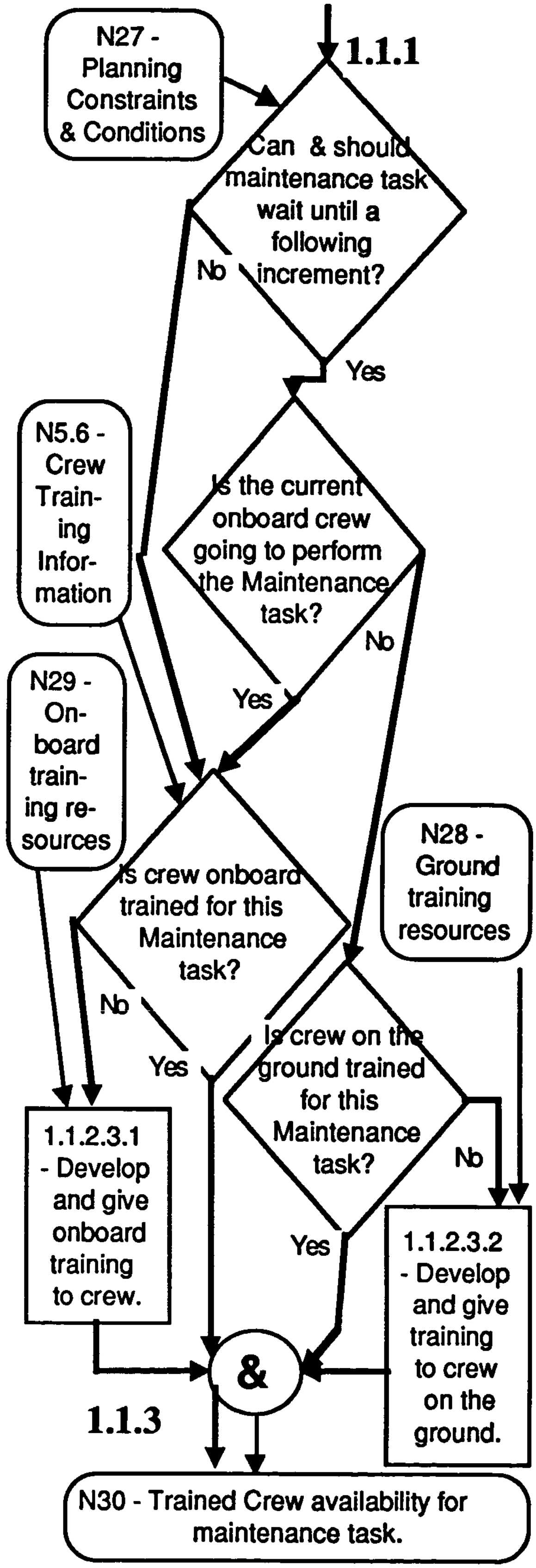
1.1.2.3 - Determine level of crew training: The maintenance operator utilizes the Training Administration System to determine the training completed by the crew member. Additionally the operator may discuss with the instructor that taught the crew member a specific class or set of instruction to farther determine the crew members proficiency at a given task. In addition, a review of past mission accomplishments/assignments and job specialties may give insight into determining the level of crew member training.

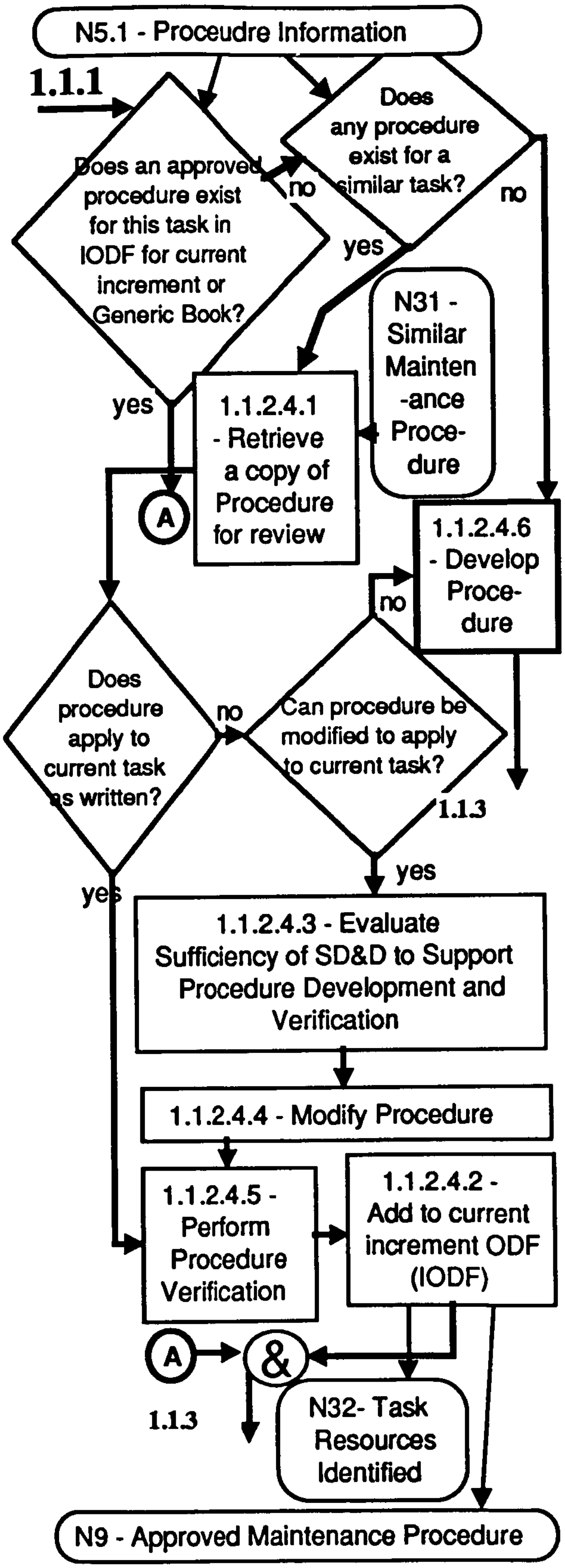
1.1.2.3.1 - Develop and give onboard training to crew: The ground controllers/training personnel may need to develop/administer on-orbit training to crew members. The prime method will be on-orbit on-the-job-training (OJT). Another method uses a lesson plan that allows the crew member to be trained on-orbit by studying a ground developed and up linked lesson by performing the related tasks in a non-intrusive/destructive manner.

1.1.2.3.2 - Develop and give training to crew on the ground: The crew training is grouped into generic training and task specific training. The generic training is a set of training that develops skills and knowledge that can be used to complete many similar type tasks; however, specific training may be necessary for training that is not included in generic and is required for proficiency. The ground training will be given to the crew members using training manuals, classroom instruction, mock-ups, vendor facilities, or other NASA Centers.

1.1.2.4 - Determine if procedure, primary and ancillary SD&D exists: This process addresses the steps taken by maintenance personnel, both on- and off-console, prior to scheduling and execution of a maintenance activity, to assess whether a previously developed and approved maintenance procedure, possibly from a previous increment, is applicable and complete to address the maintenance need present in the increment in work.

If the previously developed and approved maintenance procedure is not adequate, this process outlines the appropriate actions required to perform additional research, to update the procedure to bring it into compliance with the demands of the annotate the list of source and present (in work) increment, and to





ancillary technical data used to create the procedure and clarify its contents.

1.1.2.4.1 - Retrieve a copy of Procedure for review: This involves obtaining a copy of the procedure as it appears in the ODF, if it exists.

1.1.2.4.2 - Add to current increment ODF (IODF): The procedure as finally written is put into the ODF for the upcoming increment. This is a formal process controlled by the Procedure Documentation, Authoring and Control system.

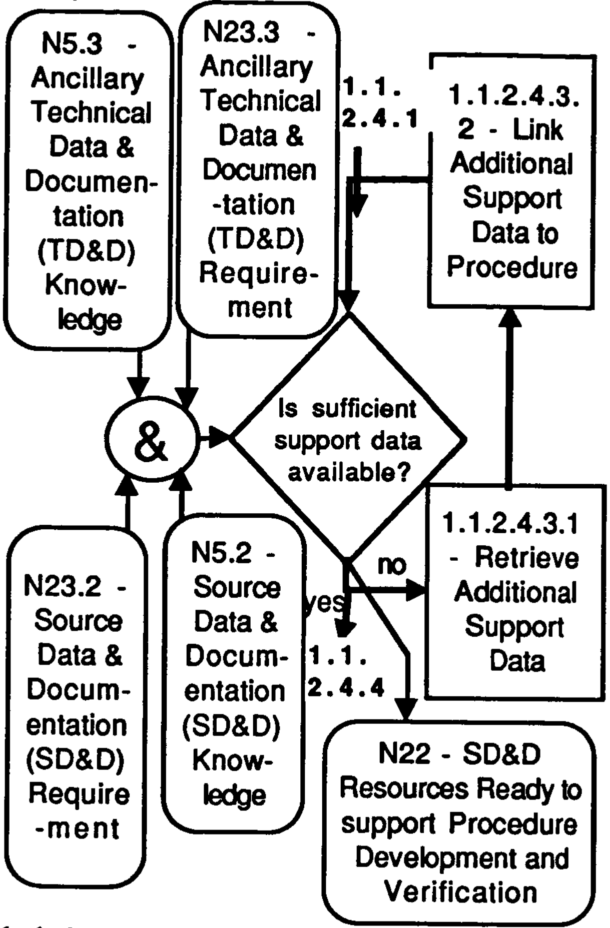
1.1.2.4.3 - Evaluate Sufficiency of Support Data & Documentation (SD&D) to Support Procedure Development and Verification: The SD&D is judged for task sufficiency. The purpose is to see if the activity has enough supporting information that most foreseeable problems or questions can be readily handled. If the SD&D is not sufficient, then an effort is made to obtain the "missing" information; either within the CCC or from the program office resources, i.e., information systems, data bases, personal interfaces, data that the original equipment manufacturer may have, etc. The SD&D may be used for support of the verification of the procedure even though it is not used directly in the procedure.

1.1.2.4.3.1 - Retrieve Additional Support Data: If more Support Data & Documentation is needed then that information must be obtained. See 1.1.2.4.3 for sources.

1.1.2.4.3.2 - Link Additional Support Data to Procedure: The SD&D must be linked with pointers to the activity and its procedure. The data may be part of the procedure or may be appended to the activity.

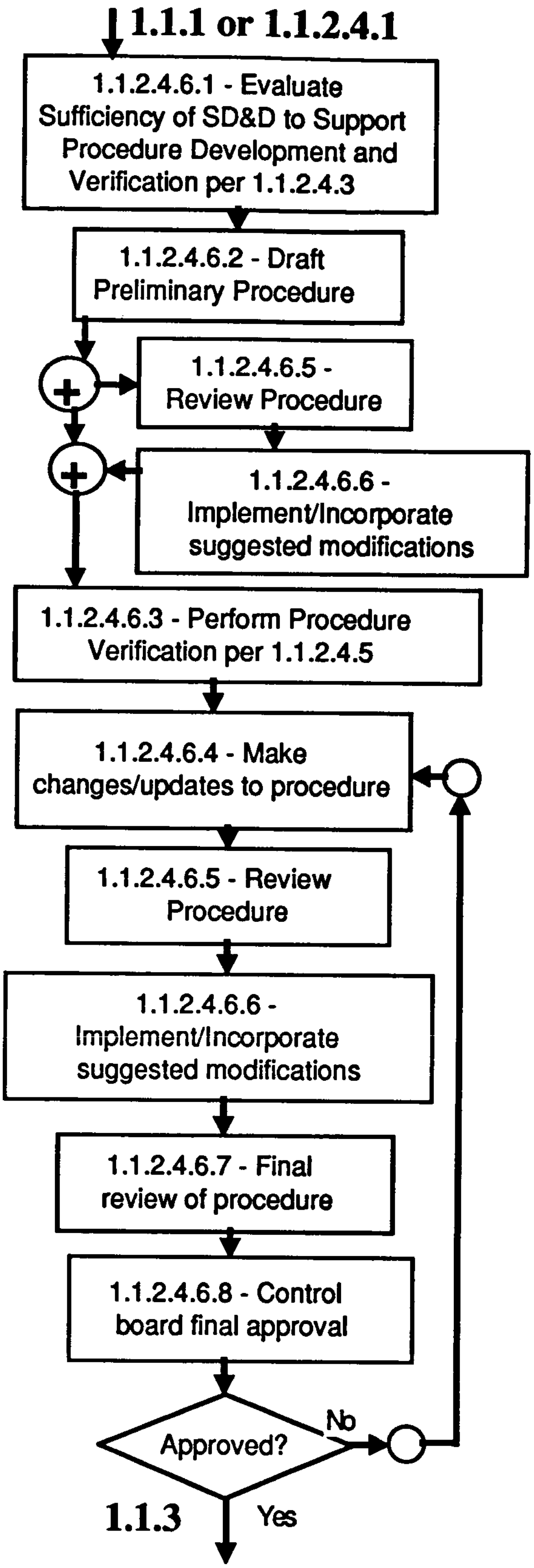
1.1.2.4.4 - Modify Procedure: The procedure, if not appropriate for the maintenance activity, is changed until it is appropriate to the task. This includes passing all verification requirements.

1.1.2.4.5 - Perform Procedure Verification: When the procedure has been written or composed then the procedure needs to be evaluated to see if it will accomplish what is intended. To do this the procedure under goes a verification. Procedure verification may be accomplished by analysis or by demonstration.



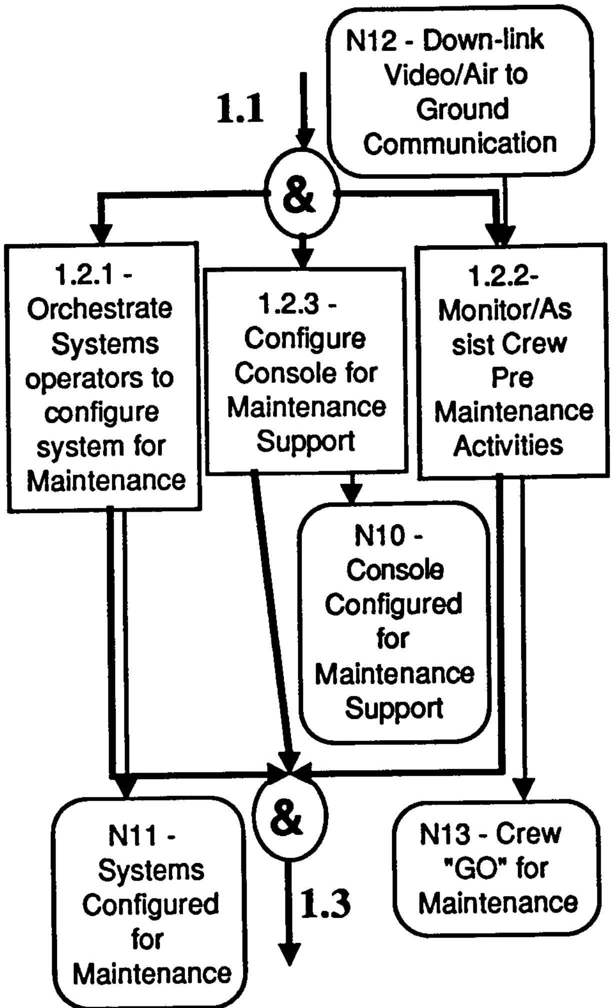
1.1.2.4.6 - Develop Procedure: If there is not an existing procedure that can be modified to meet the maintenance activity's requirements, then a procedure is developed from scratch. The Consolidated Maintenance, Inventory & Logistics Planning (CMILP) system is the tool used to pull together the information for the procedure. The information as completed in CMILP is then passed to the Procedure Documentation, Authoring and Control system for the formal procedure development, verification and base lining under configuration management.

1.1.2.4.6.1 - Evaluate Sufficiency of SD&D to Support Procedure Development and Verification: See 1.1.2.4.3 - Evaluate Sufficiency of SD&D to Support Procedure Development and Verification

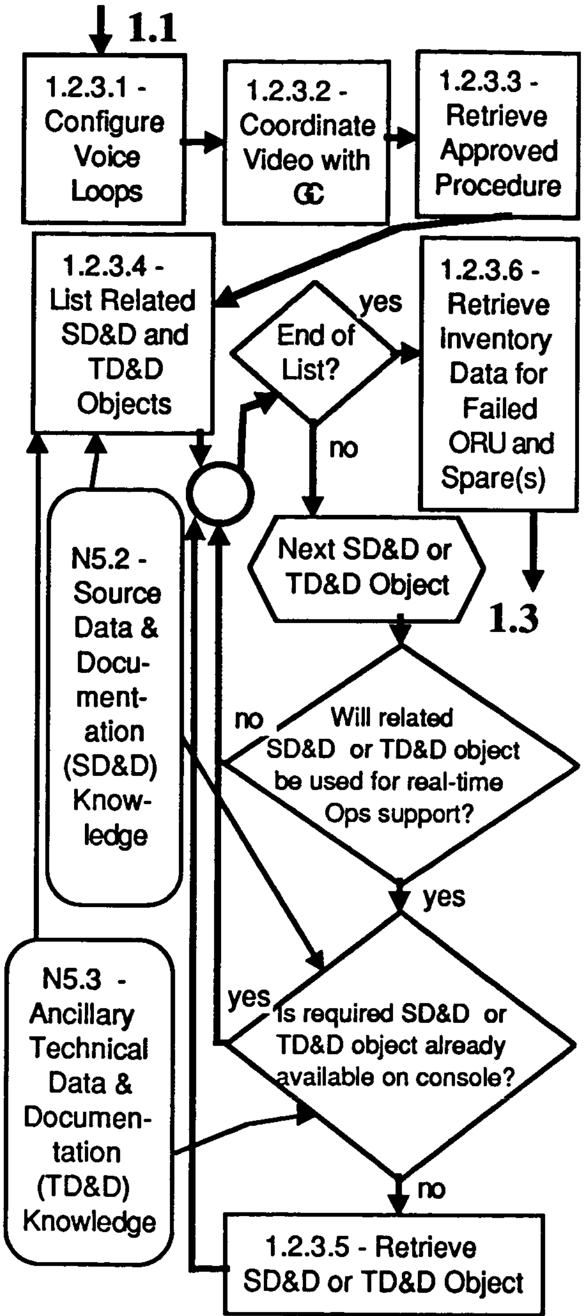


1.1.2.4.6.2 - Draft Preliminary Procedure: Develop Procedure;

except for verification and base lining within the configuration system.
1.1.2.4.6.3 - Perform Procedure Verification: See 1.1.2.4.5 - Perform Procedure Verification
1.1.2.4.6.4 - Make changes/updates to procedure: The procedure is modified based upon verification activities to accomplish or better accomplish the objectives of the procedure.
1.1.2.4.6.5 - Review Procedure: The review is conducted against the Support Data & Documentation, the Logistics Support Analysis Records used in the production of the draft preliminary procedure and the standards for procedures.
1.1.2.4.6.6 - Implement/Incorporate suggested modifications: This is modifying the procedure to include the recommendations revealed within the verification and configuration base lining process.
1.1.2.4.6.7 - Final review of procedure: This is the completion of the review and verification process just before the procedure goes under formal configuration management.
1.1.2.4.6.8 - Control board final approval: The procedure becomes a configuration controlled procedure at this point. The process for modification and verification may need to be repeated if the final control board approval is not forth coming or minor changes required.
1.1.3 - Maintenance Activity Planning: This is providing to the Operations Planner all of the information needed to get the maintenance activity a position of the time line. The preceding process should have produced all the needed information such that this process is straight forward. The internal Operations Planner process is not covered.
1.2 - Perform Pre Maintenance Activities: This includes all of the sub process to prepare for maintenance. This is after the planning of the maintenance and the activities associated with getting to the point of actually doing the maintenance.



1.2.1 - Orchestrate Console Operators to Configure System for Maintenance: Prior to execution of a repair action, the item/system being maintained as well as other systems may need to be reconfigured or verified in a certain configuration.
1.2.2 - Monitor/Assist Crew Pre Maintenance Repair Activities: The console conducting the on-orbit maintenance will coordinate the procedural details of task execution of any pre-maintenance procedure being executed by the crew.
1.2.3 - Configure Console for Maintenance Support: OSO prepares the console support tools to present all information required by him or her to support the crew and the rest of the Flight Control Team while the crew is performing maintenance.



1.2.3.1 - Configure Voice Loops: Prior to the start of the maintenance activity, the OSO configures the Digital Voice Information System keyset to contain all voice loops required to maintain communications with other MCC personnel supporting the maintenance activity.

1.2.3.2 - Coordinate Video with Ground Systems Mission Controller (GC): Prior to the start of the maintenance activity, OSO will ensure that GC will be providing air-to-ground video during maintenance operations.

1.2.3.1 - Retrieve Approved Procedure: Prior to the start of the maintenance activity, the Electronic Documentation Processing (EDP) server is used to retrieve a copy of the approved maintenance procedure for review and use as a checklist.

1.2.3.4 - List Related SD&D and TD&D Objects: For each procedure used during a maintenance activity, the list of reference information which was used in the creation of the procedure (the DSI-Data Source Index) is reviewed, as well as a list of any additional data (Ancillary TD&D) that will illustrate, describe in detail, or otherwise amplify the operator's understanding of the procedure methodology or the hardware involved.

1.2.3.5 - Retrieve SD&D or TD&D Object: Once the decision is made as to what information is needed for quick reference in support of maintenance execution, the Consolidated Maintenance, Inventory and Logistics Planning system is used to retrieve the Support Data and Documentation and/or Technical Data and Documentation for use on console.

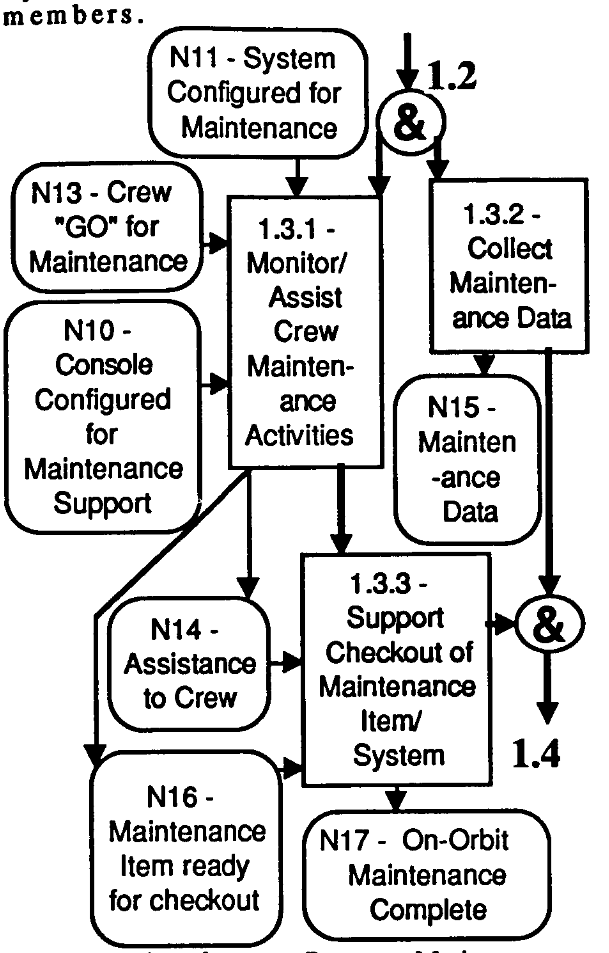
1.2.3.6 - Retrieve Inventory Data for Failed ORU and Spare(s): TBD - The mechanics of this has not been established yet.

1.3 - Perform Maintenance Activity: The actual execution or conduct of the maintenance activity takes place within this process.

1.3.1 - Monitor/Assist Crew Maintenance Activities: The console conducting the on-orbit maintenance monitors/assists the crew during the maintenance activity.

1.3.2 - Collect Maintenance Data: This process addresses the activities involved with producing historical documentation on the conduct of on-orbit maintenance.

1.3.3 - Support Checkout Maintenance Item/System: When the maintenance item/system physical interfaces have been re-established and verified, the console conducting the on-orbit maintenance requests that a system checkout be performed by Ground Controllers/Crew members.



1.4 - Perform Post Maintenance Activities: This includes three major processes and they are:

-1.4.1 - Coordinate w/console operators to configure system after Item Repair

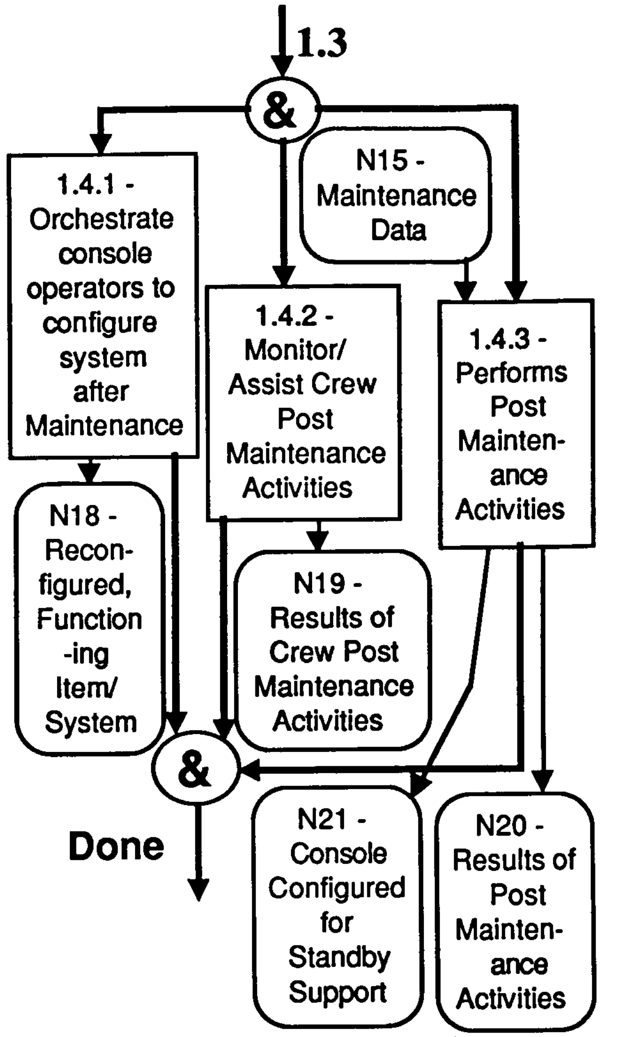
-1.4.2 - Monitor/Assist Crew Post Item Repair Activities

-1.4.3 - OSO Performs Post Item Repair Activities

1.4.1 - Orchestrate console operators to configure system after item repair: This is any processes/actions of coordinating with the console operators and/or crew (through the console operators) to get the maintenance item/system back in the operating configuration.

1.4.2 - Monitor/Assist Crew Post Maintenance Activities: The maintenance console operator monitors/assists the crew during the post item repair activity.

1.4.3 - Perform Post item repair Activities: This is composed of four



major processes/actions. They are:

-1.4.3.1 - Review/Modify Procedure against the as Executed Task

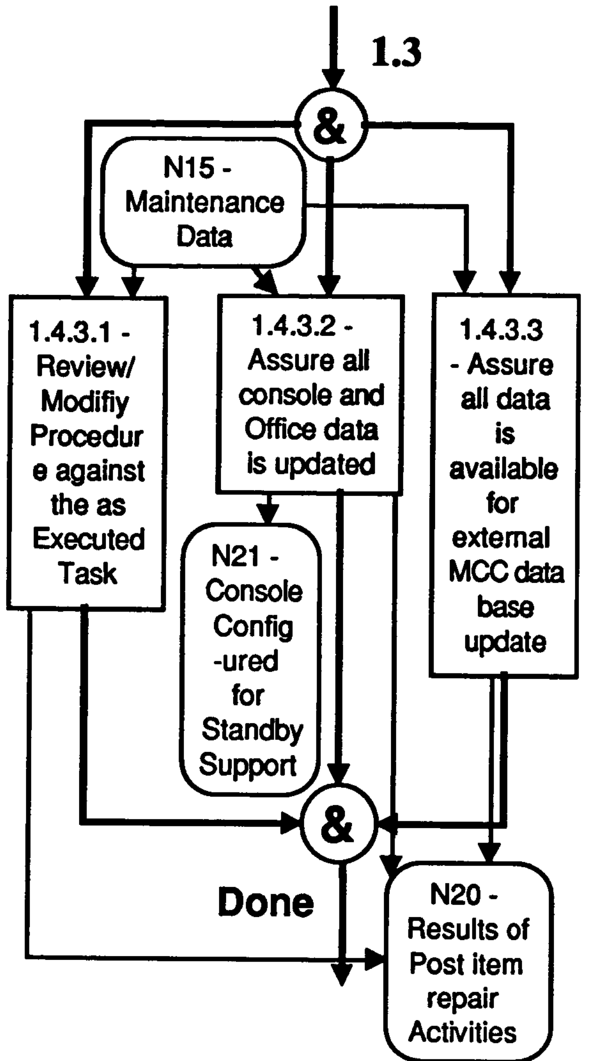
-1.4.3.2 - Assure all console and Office data is updated

-1.4.3.3 - Assure all data is available for external data base update

1.4.3.1 - Review/Modify Procedure against the as Executed Task: Annotations are made of deviations of the as-executed procedure from the official procedure.

1.4.3.2 - Assure all console and Office data is updated: This is updating any of the console products, CMILP resident data or data at the office location.

1.4.3.3 - Assure all data is available for external MCC data base update: This is updating any of the data that flows to external MCC organizations.



Biography: Mr. Zingrebe is a SOLE Life Member and member of National Council on Systems Engineering, Alpha Pi Mu, and Phi Kappa Phi. Mr. Zingrebe is a Barrios group lead in the Johnson Space Center, Mission Operations Directorate, Space Station Systems Division, Environmental Systems and Maintenance Branch. Mr. Zingrebe's fields of experience include Systems Engineering, Integration, Design, and Modeling; Production, Maintenance, and Facilities Engineering; Aerospace Operations and Development; Integrated Logistics Support; University Instruction; and Consulting. Mr. Zingrebe has worked for or on projects for Barrios Technology; Rockwell Space Operations; NASA; SOFEC Defense Systems; Navel Facilities Engineering Command; BDM; U.S. Army, TCATA; U.S.A.F., Range Applications Joint Program Office, Ballistic Missile Office, Institute of Technology, and Office of Scientific Research; TRW; General Motors Defense Systems; U. of Houston, Industrial Engineering, Operations Management, and Hilton College of Hotel and Restaurant Management; U. of Texas, School of Nursing; and Clorox Co. Mr. Zingrebe has an M.B.A., Operations Management; M.S. and B.S., Industrial Engineering; from the University of Houston and a B.S., Packaging Engineering from Michigan State University

LEADING EDGE SOFTWARE SUPPORT

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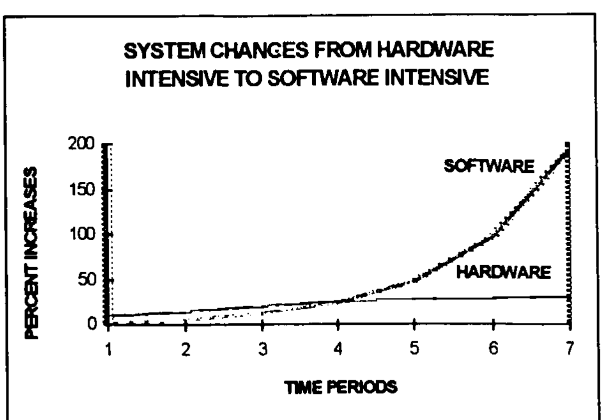
Abstract

The purpose of this paper is an attempt to get the reader to recognize that different requirements that are surfacing and to be proactive in achieving successful support of these systems. This paper will identify areas of concern and present some areas of focus applicable to the development and support of software intensive systems.

Introduction

Over the past few years, major weapon systems and electronic systems have become software intensive. A recognizable pattern has occurred whereby system changes in hardware are not as dramatic as those encountered in the area of software. This is very apparent for space systems which are positioned, activated and repaired (limited) via software programs. The following graph, not drawn to scale, depicts a graphical representation of the changing from hardware intensive to software intensive systems found today.

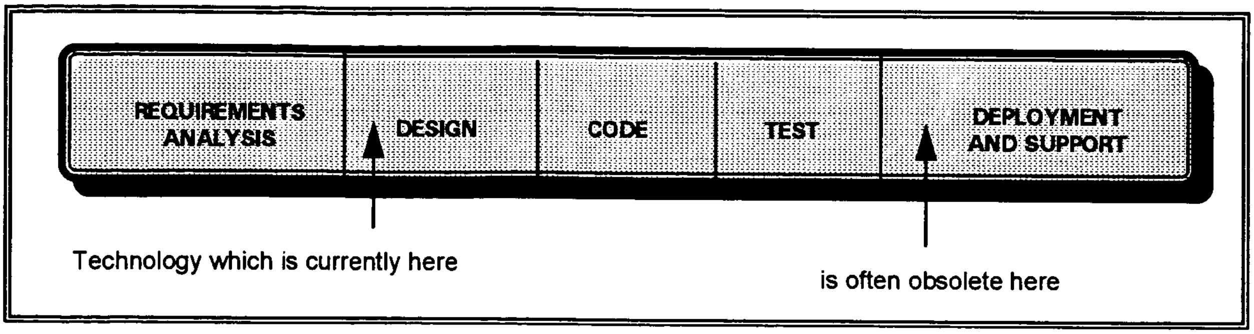


Due to the rapid changes that occur in today's High Technology systems, it is imperative that individuals let loose of the "Traditional ways" of doing business and focus on what is needed to properly develop, implement and support these High Technology systems which are becoming more prevalent in today's space systems. Even though the goals of the "traditional" processes and methodologies remain relatively unchanged, the work effort expended on the the Space Station program has resulted in recognizing that issues and concerns have surfaced that make it imperative to "re-assess" the way that development and support of software needs to be conducted on current and future Space Programs.

Overview

In years past, the amount of software written constituted a small percent of system development. This effort focused upon support of the system in terms of repair and "checking the health" of the system. If the software had errors in it, it didn't make a lot of difference in terms of achieving the mission. Software was written for diagnostic testing purposes. This is not what is being experienced in today's high technology arena. Computer and its associated software technology is undergoing rapid advancement. The following drawing shows this lag in time and technology between the design of the system and the deployment of the system.

This is not the case anymore, computer and associated software technology is advancing so rapidly that:



Space systems represent undertakings of massive proportions that introduce requirements, concerns and constraints resulting in new applications of existing procedures and methodologies, including support. This realization came about on the current Space Station program.

For example, launching the shuttle requires volumes upon volumes of data and information to assess the safety of the propose launch, all of this is accomplished at "Real Time" speed. If a major problem develops, it is possible to scrub the launch with scant seconds to spare.

With planned manned space systems you don't have this type of luxury, with software controlling of having a major part in the control of on-board systems, if a "software failure" occurs there exists a large potential probability of loss of life. It is not possible to "cancel".

Reliability and maintainability are used in software development; however, quite a few individuals try to view software development and associated analyses in the same light as hardware.

When considering software design and development and associated analyses for assisting in the software Supportability for space systems, it is imperative to recognize that there is a separation between software development and hardware development. Due to the nature of the operational scenario, not treating software as a separate entity will not completely satisfy the determination of all Supportability requirements for space systems. The following table depicts the differences in the difference between maintainability and reliability for hardware and software.

	RELIABILITY	MAINTAINABILITY
HARDWARE	probability that a system or product will perform its intended function under defined conditions at designated times for specified operating periods.	inherent characteristic of a design or installation that determines the ease, economy, safety, and accuracy with which maintenance actions can be performed.
SOFTWARE	probability of failure free operation of a computer program in a specified environment for a specified time	ease at which software can be understood, corrected, adapted, and/or enhanced.

Definitions

1. *Correctness* - Extent to which a program satisfies its specification and fulfills the customer's mission objectives.

2. *Efficiency* - Amount of computing resources and code required by a program to perform its function.

3. *Integrity* - Extent to which access to software or data by unauthorized persons can be controlled.

4. *Interoperability* - Effort required to couple one system to another.

5. *Maintainability* - Effort required to locate and fix an error in a program.

6. *Portability* - Effort required to transfer the program from one platform and/or software system environment to another.

7. *Reliability* - Extent to which a program can be expected to perform its intended function with required precision.

8. *Reusability* - Extent to which a program (or part of a program) can be reused in other applications.

9. *Testability* - Effort required to test a program to ensure that it performs its intended function.

10. *Usability* - Effort required to learn, operate, prepare input and interpret output of a program.

As with hardware development, there are a number of areas that need to be addressed when developing and assessing support requirements over the life of a system. The following chart delineates some of the components of software development and support that need to be considered to arrive at effective software development and support for high technology space systems.

SPACE SYSTEMS CONCERNS/ISSUES
SOFTWARE QUALITY
SOFTWARE RELIABILITY
SOFTWARE SAFETY
SOFTWARE MAINTENANCE
MAINTAINABILITY
HUMAN FACTORS
ROBOTICS
REPAIR SCENARIOS

What follows is a brief description of and some guidelines for each of the aforementioned areas.

Software Quality

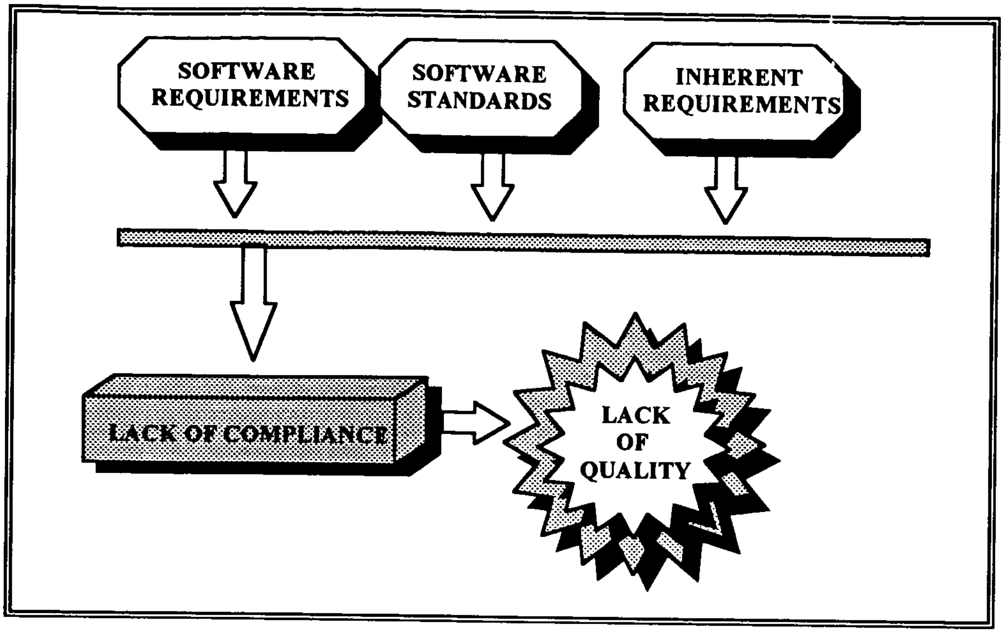
Quality is ever present in everything that we do. No one individual works in a total vacuum, we all have people that rely upon what we do. Software quality is applied throughout the software development process, it is not something we look at after writing the code.

Software quality is comprised of the following three (3) components:

1. Software requirements - These represent the starting block from where quality is measured. These make up the program definition.

2. Standards - These tell you how to plan and carry out the software development.

3. Inherent Requirements - These represent "Just good, smart" developmental practices that support definitive requirements.



Software Reliability

This represents an important component of a software program's overall quality. software reliability can be measured directly and estimated utilizing historical and developmental data. Software reliability is defined as the *Probability of failure free operation of a computer program in a specified environment for a specified time.* Failure can be a difficult term to grasp, failures can range from something easy to correct or something catastrophic. Correction of one failure can induce multiple errors (this happens when one introduces a "Band-Aid" fix to software.

Hardware-related reliability models are based on failures due to wear whereas software failures can be traced to design or implementation problems. Software reliability is usually measured in terms of:

$$\frac{\text{\# of Defects}}{\text{K Lines of Code}}$$

Software Safety

Software safety needs to be looked at intently when developing a computer program, this is especially true when the software is used to control safety critical processes. An undetected fault in a computer-based control or monitoring system could result in significant human injury, loss of life, or tremendous financial tragedy. When software is used as part of the control system, complexity can increase by a significant order of magnitude.

Design faults induced by human error - which can be uncovered and eliminated in hardware-based conventional control - become much more difficult to uncover when software is used. Software safety is a quality assurance activity that focuses on the identification and assessment of potential hazards that may impact software negatively and can cause an entire system to fail. By identifying hazards early in the software development process, software design features can be specified that will either eliminate or control potential hazards.

Hazards are identified and categorized by criticality and risk. To be considered effective, the software needs to be analyzed in the context of the entire system. You do not separate the software from the system. It should be noted that people are components of the entire system.

I.E., a subtle user input error may be magnified by a software fault to produce control data that improperly positions a robotic arm. If a set of external environmental conditicns are met (and only if they are met), the improper positioning of the robotic arm could cause a disastrous failure.

Software Maintenance

There are four (4) activities that are that comprise software maintenance:

1. Corrective Maintenance - includes the diagnosis and correction of one or more errors. This activity occurs because it is unreasonable to assume that software testing will uncover all latent errors in a large software system. With systems operating in orbit, it is extremely difficult to ascertain all the problems that could occur prior to becoming operational. Errors that occur in orbit will need to be relayed back for proper code correction. The possibility exists that some errors would not be to be duplicated on earth.

2. Adaptive Maintenance - modifying software to properly interface with a changing environment. This occurs due to the rapid changes that occur within the computing environment. New pieces of hardware, new operating systems, peripheral equipment and other system elements are frequently upgraded or modified. When designing a major space system, the current method is modularity. Here it can be seen that hardware and systems will develop over a period of time and that changes could occur rapidly in the beginning of system development resulting in the probability of unanticipated requirements and needs. These would result in adapting the software to coincide with system changes.

3. Perfective Maintenance - this accounts for the majority of all effort expended on software maintenance. This activity deals with incorporating enhancements to the software requested by users. I.E., new capabilities or modifications to existing functions.

4. Preventive Maintenance - this activity is characterized by reverse engineering and re-engineering techniques. This activity occurs when software is changed to improve future maintainability or reliability, or to provide a better basis for future enhancements.

It should be noted that analogies between software and hardware maintenance can be misleading. As was pointed out previously, software, unlike hardware, does not wear out; therefore, any major activity associated with hardware maintenance - replacement of worn or broken parts -does not apply.

Adaptive and perfective maintenance tasks are the same tasks applied during the development phase of the software engineering process. To adapt or perfect, you need to determine new requirements, redesign, generate code, and test existing software. This is known as maintenance.

Problems:
Most problems associated with software maintenance can be traced to deficiencies in the way software was planned and developed. The following delineates what usually causes problems. These need to be kept in mind when developing software:

1. It is difficult or impossible to trace the evolution of the software through many versions or releases. Changes therefore need to be adequately documented.

2. It is often difficult or impossible to trace the process through which software was created. To preclude this document the process.

3. It is often extremely difficult to understand "someone else's" program. The difficulty increases as the number of elements in a software configuration decreases. Maintain the software configuration.

4. "Someone else" is often not around to explain. Do not build a "single point failure" into the software development.

5. Documentation doesn't exist or is incomplete. It is important to recognize that documentation is necessary but it must also be understandable and consistent with source code to be of any value.

6. Most software is not designed for change. Modifications to software are difficult and error-prone.

Maintainability

Maintainability can be defined quantitatively as the ease with which software can be understood, corrected, adapted, and/or enhanced. Maintainability is affected by many factors. These factors include: inadvertent carelessness in design, coding, testing and poor software configuration. It is easy to understand the need for standardization of methodology employed, resources and approach. If software is viewed as a system element that will inevitably undergo change, the chances that maintainable software will be produced are likely to increase substantially.

Software Maintainability can be difficult to quantify; however, it can be assessed indirectly be considering attributes of the maintenance activity. The following delineates maintainability metrics that relate to the effort expended during maintenance:

1. Problem recognition time
2. Administrative time
3. Maintenance tools collection time
4. Problem analysis time
5. Change specification time
6. Active correction (or modification) time
7. Local testing time
8. Global testing time
9. Maintenance review time
10. Total recovery time

At each level of software engineering, maintainability should be considered. Consideration should be given to: areas of future enhancements and potential revisions; software portability; system interfaces that might impact software maintenance; data design, architectural design, procedural design, and interface design are considered for ease of modification and overall design quality. review code to stress style and internal documentation.

Maintenance Side Effects:

Design documentation and testing can help eliminate error, but there is still the possibility of encountering Maintenance side effects. When viewing software maintenance, the term "side effects" implies an error or other undesirable behavior that occurs as a result of modification. There are three (3) major categories for side effects.

Coding Side Effects:

A simple change to a single statement can sometimes have disastrous results. Change invites error and error always to problems. Communication to machines is accomplished through programming language source code. Although every code modification has the potential for introducing errors, the following set of changes tend to be more error-prone than others:

1. A subprogram deleted or changed.
2. A statement label is deleted or modified.
3. an identifier is deleted or modified.
4. changes are made to improve execution performance.
5. File open or close is modified.
6. Logical operators are modified.
7. design changes are translated into major code changes.
8. Changes are made to logical tests of boundary conditions.

Data Side effects:

During maintenance modifications are often made to individual elements of a data structure or to the structure itself. When data change, the software design may no longer fit the data and errors can occur. Data side effects occur as a result of modifications made to the software information structure.

The following changes in data frequently result in side effects:

1. redefinition of global and local constants
2. redefinition of record or file formats
3. increase or decrease in the size of an array or a higher-order data structure
4. modification to global data

5. reinitialization of control flags or pointers
6. rearrangement of arguments for I/O or subprograms

Data side effects can be limited by thorough design documentation that describes data structure and provides a cross reference that associates data elements, records, files, and other structures with software modules.

Documentation Side Effects:

Maintenance needs to focus on the entire software configuration and not on source code modification alone. Documentation side effects occur when changes to source code are not reflected in the design documentation or user-oriented manuals. Whenever a change to data flow, design architecture, module procedure, or any other related characteristic is made, supporting technical documentation must be updated. Side effects occur in subsequent maintenance efforts when an innocent perusal of technical documents leads to an incorrect assessment of software characteristics.

If modifications to the executable software are not reflected in the user documentation, side effects are guaranteed. Documentation side effects can be reduced substantially if the entire configuration is reviewed prior to re-release of the software.

Maintenance is the last phase in the software engineering process, accounting for the majority of all dollars spent on computer software. The result is that the amount of effort and resources expended on software maintenance is growing. Two methods can assist in the maintenance process: (1). Reverse engineering - this extracts design information from program source code when no other documentation exists. (2). Re-engineering - takes the information obtained and restructures the program to achieve higher quality and, therefore, better maintainability in the future.

Human Factors

When developing systems it is extremely important to note Individual skill level differences, personality variations, and behavioral distinctions among users of a computer-based system.

An interface acceptable for one skill level might be inadequate for another. The same interface for two individual of the same skill level but different personalities might be user friendly for one but unfriendly to the other.

An interactive computer-based system rarely enables a user to do something entirely new. In most cases, the system is built to automate (and thereby improve) certain tasks that were previously performed by hand or some other approach. This is very useful in hazardous environments. I.E., external repair of a space system can be accomplished by a technician without venturing outside the craft using computer controlled robotics Ideally, the new technology enables a user to perform tasks better, faster, more efficiently, more accurately, more safely, or less expensively.

Even with interactive computer-based systems, the following tasks are almost always performed:

Communication tasks - activities that enable information to be transferred from one individual to another.

Dialog tasks - activities that enable the user to direct and control interaction with the computer-based system.

Cognitive tasks - activities that are performed once information has been obtained; activities associated with the function of the system.

Control tasks - activities that allow the user to control information and cognition and order process through which other generic tasks occur.

Interfaces can range from simple menus to icons, windows, touch screens, and pointing devices.

Simple menus provide the user with an overall context and is less error prone that typing command lines. If comprised of numerous layers, simple menus can be tedious to use since the user needs to transverse through the different layers to achieve the goal. It is easy to see that this approach is not efficient for running space systems where time is a critical factor.

With sophisticated hardware being developed, it is imperative that better interfaces be utilized. To support today's high technology systems, the following improvements in interfaces have evolved:

1. Different types of information can be displayed simultaneously, enabling the user to switch context without losing visual connection with other work. Windows enables the user to perform many communication and cognitive tasks efficiently.

2. Many different interactive tasks are available through *pull-down* menu schemes. These menus allow users to perform control and dialog tasks in a facile manner.

3. Use of graphical icons, pull-down menus, buttons, and scrolling techniques reduce the amount of typing. This can increase the interaction efficiency.

Multitasking, window-oriented, point and pick interfaces make the human computer interface more friendly, faster and easier only if careful design of the interface is conducted.

Design Issues

During the design of a user interface, four common design issues almost always surface: System response time, user help facilities, error information handling, and command labeling.

1. System response time - this is measured from the point at which the user performs some control action until the software responds with the desired output or action. Response time possesses two very important variables: length and variability.

Length - this represents the length of time associated with a response. Too short a response time can cause the user to rush and possibly make mistakes. Too long a response is not efficient.

Variability - this refers to the deviation from average response time. Varying the response time with wide margins can cause stress on the part of the user. There is enough stress being in orbit without adding more. A consistent response time is beneficial for the user.

2. Help Facility - Interactive systems require some sort of on-line help that enable the user to get a question answered or resolve a problem without leaving the interface.

The following represent design issues when considering a help facility:

a. Will help be available for all system functions and at all times during system interaction?

b. How will the user request help? (Help menu, special function key, HELP command).

c. How will the help be represented? (Separate window, reference to a printed document, one or two line suggestion produced in a fixed screen).

d. How will the user return to normal interaction? (Return button displayed on the screen, function key, or control sequence)

e. How will the help information be structured? (Flat structure where all information is accessed through a keyword, layered hierarchy of information - provides increasing detail as the user proceeds into the structure, hypertext).

3. Error Messages - these are delivered to the user of interactive systems that something has gone awry. If poorly designed/displayed, error messages impart useless or misleading information and serve only to increase user frustration. Most users have seen error messages that present a failure type and a code [i.e., System Failure -- 23S]. This indicates a failure has occurred but not what it is or even where to look. Every error message or warning should have the following characteristics:

The message should describe the problem in jargon that the user can understand.

The message should provide constructive advice for recovering from the error.

The message should indicate any negative consequences of the error so that the user can check to ensure that they have not occurred (or correct them if they have).

The message should be accompanied by an audible or visual cue. This can be a beep or a momentary flash of a identified "error color".

The message should be nonjudgmental. Do not place blame on the user.

Interface Design Guidelines:

There are three categories of human computer interface design guidelines - general interaction, information display, and data input.

General Interaction - this area crosses into information display, data entry, and overall system control. The following should be considered:

Be consistent - use a consistent format for menu selection, command input, data display, and other functions that occur.

Offer meaningful feedback - provide the user with visual and auditory feedback to ensure that two-way communication (between user and interface) is established.

Ask for verification for any non-trivial destructive action - if the user requests the deletion of a file, indicates that substantial information is to be overwritten, or asks for termination of a program, an "Are you sure ...?" message needs to appear.

Permit easy reversal of most actions.

Reduce the amount of information that must be memorized in between actions - the user should not be expected to remember a list of items so that they can be reused in a subsequent function. Memory load should be minimized.

Seek efficiency in dialogue, motion, and thought - Keystrokes should be minimized, distance a mouse travels between picks needs to be considered, the user should never be placed in a situation where they need to ask "What does this mean?".

Forgive mistakes - the system should protect itself from user errors that might cause it to fail.

Categorize activities by function and organize screen geography accordingly - One key benefit of a pull-down menu is the ability to organize commands by type.

Provide help facilities that are context-sensitive.

Use simple action verbs or short verb phrases to name commands - a lengthy command name is more difficult to recognize and recall. It can take up space on a menu list.

Information Display:

Information is displayed in many different ways - with text, pictures, and sound; by placement, motion, and size, using color, resolution; and even by omission. Information needs to satisfy the needs of the user; therefore, it can not be incomplete, ambiguous, or unintelligible. The following guidelines focus on information display:

Display only that information that is relevant to the current context - the user should not have to wade through extraneous data, menus, and graphics to obtain information relevant to a specific system function.

Don't bury the user with data - use a presentation format that enables rapid assimilation of information. Graphs or charts should replace voluminous tables.

Use consistent labels, standard abbreviations, and predictable colors - the meaning of a display should be obvious without reference to some outside source of information.

Allow the user to maintain visual context - If graphs are, scaled up and down, the original image needs to be displayed constantly so that the user understands the relative location of the portion of the image currently being viewed.

Produce meaningful error messages.

Use windows to compartmentalize different types of information.

Consider the available geography of the display screen and use it efficiently.

Data Input:

Much of the user's time is spent on providing system input. This can be accomplished by means of a keyboard, mouse, digitizing tablet, and even voice recognition. The following guidelines focus on data input:

Minimize the number of input actions required by the user - reduce the amount of typing required by the user. This can be accomplished by using a mouse to select from predefined sets of input; using a "Sliding scale" to specify input data across a range of values; using "macros" that enable a single keystroke to be transformed into a more complex collection of input data.

Maintain consistency between information display and data input - the visual characteristics of the display (e.g. text, color, size, placement) should be carried over to the input domain.

Allow the user to customize input - an expert user might decide to create custom commands or dispense with some types of warning message and action verification.

Interaction should be flexible but also tuned to the user's preferred mode of input.

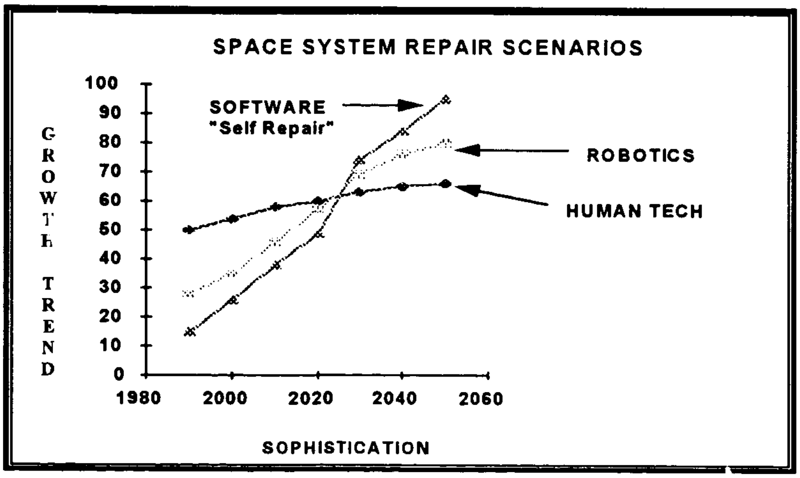
Deactivate commands that are inappropriate in the context of current actions - this protects the user from attempting some action that could result in an error.

Let the user control the interactive flow - the user should be able to jump unnecessary actions, change the order of required actions (where possible) and recover from error conditions without existing from the program.

Provide help to assist with all input actions.

Repair Scenarios

When analyzing space systems some of their peculiarities surface, one are is that of their evolving "repair scenarios". The following chart depicts the growth trend with regard to who or what accomplishes the repair:



Repairs currently being performed by human technicians will be transferred to robotics and eventually we will see a large degree of software "self-repair" being accomplished (which is facilitated by reusable software and modularity). This allows on-board personnel to focus their efforts on the primary mission of the space system.

Robotic Tasks

Due to the ever present life threatening environment outside the station, robotic tasks are to be used where practical and cost effective. Markings and lights need to be provided to support computer vision and other vision requirements. The plan is for evolving space station design incorporating increased utilization of autonomous Robotic devices.

The ultimate goal is for all EVA tasks to be performed by Robots, until that time, humans need to journey outside the space craft into probably the most dangerous and unfriendly environment known to man and assist Robots in performing necessary tasks.. This means that space systems will evolve into software intensive systems.

Bottom Line

It seems apparent that software developers need to make more use of "reusable" code. This represents code that is written once and possesses multiple uses. As more space systems are developed, code written and debugged for one system can be "re-used" on other systems. This demonstrates the need for standardization and modularity of software. Standardization of parts (hardware application) has been in effect for a number of years.

Also, there needs to be more work done in the area of artificial intelligence in terms of software being able to maintain and correct itself. This can be seen if one understands that space system software is embedded in the control/monitoring subsystems for orbit-sustaining critical mechanical and electronic systems.

The growth trend for the repair scenario on space systems is more toward robots and self-repairing software. The space station's purpose if for materials research and life sciences research. It is not the intent of on-board personnel to deviate from this and spend long hours on effecting repairs. Therefore, design and Supportability requirements identification via LSA need to keep pace with the rapidly changing advances in technology.

Space systems exist in a very hostile environment where information flow is very important and time critical. These software systems are real-time systems that must integrate hardware, software, humans and database elements. Real-time systems generate some action in response to external events. To accomplish this, they perform high speed data acquisition and control under severe time and reliability constraints.

Although all software must be reliable, real-time systems (especially those in space systems) make special demands on reliability, restart capability and fault-recovery. Real-time systems process a continuous stream of incoming data. During the designing of the system, it is imperative that data will not be missed.

Real-time systems must take into account the usual software engineering factors (i.e. reliability, maintainability, human factors, etc.) but also they need to contain restart capability, fault recovery mechanisms and have built-in redundancy to ensure back-up.

This realization is just starting to surface on the Space Station program and will continue to do so on other space programs.

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ELECTRONIC VERIFICATION AT THE
KENNEDY SPACE CENTER

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Abstract

This document reviews some current applications of Electronic Verification and the benefits such applications are providing the Kennedy Space Center (KSC). It also previews some new technologies, including statistics regarding performance and possible utilization of the technology.

Introduction

As we enter into the 21st century we are finding more and more challenges and projects with even higher goals and standards. We are also finding lower budgets and a need for new levels of efficiency and innovation. Fortunately, the coming century brings with it a wealth of new ideas, perspectives, and technology. Electronic Verification and the Automatic Identification Industry are just part of this new era. With a little planning and education we will find ourselves ready to take full advantage of what the future has to offer.

Barcode applications at KSC

The benefits of an Electronic Verification (EV) system can be discussed, savings can be calculated, and all the estimates, charts, proposals, and comparisons can be done, but if the ideas are not put into practice it doesn't mean anything. The Kennedy Space Center has taken steps toward using some of this available technology. Barcodes have found their way into many different areas, from hardware and software to boxes, blankets, and badges. Any area that requires accurate tracking and accountability are looking at putting EV systems in place if possible. The world of Mission Kits is particularly interested in implementing an EV system for hardware tracking. Mission Kits are sets of hardware that are required for* shuttle missions. Some are mission specific while others are considered standard equipment. There are approximately 110 different Mission Kits used throughout the space program for various applications. The largest of these kits, the V073 kits, contains over 10,000 individual parts. Currently, efforts are being made to finish a large barcoding project for the V073, V7XX, and V8XX kits. Once completed, the barcode tracking system will provide greater visibility and status of Mission Kits within the processing flow. Supporting hardware and software are in place and the actual application of barcode labels is in its final stages with other applications scheduled.

Another benefit that is derived from the use of the barcoding system can be seen during assembly of the Mission Kits in the world of payload integration. Before EV was introduced to the warehouse, the procedure was filled with bottlenecks and opportunities for error. First, a list of required parts would be received at the warehouse, marked for kitting. A physical retrieval of all the parts listed was required as well as documentation of the hardware for accountability purposes. Once a part was removed from the shelf it had to be removed from the database as being available. Therefore, after retrieval of the hardware, the computer was updated via keyboard entry. Mistakes were made during kitting because of copy errors, illegible handwriting, misplaced parts, or in the entry of information into the computer. A study performed by RI estimated that over 10,000 errors per month could have been attributed to keystroke errors alone, during data entry in the Orbiter Processing Facilities (OPF). And since one list required several people across multiple shifts to complete, the possibility for errors was increased. With a barcode system a portable scanning unit can now be taken into the warehouse to scan in the barcode of the part retrieved. This eliminates the possibility of a copy error or the recording of an inappropriate number (OCN number for example). After the collection is complete the information on the portable scanner can then be downloaded into the computer, again removing the possibility for human error. Plus, the system can compare the downloaded information to the kit requirements and display any discrepancies. This serves as another safeguard to help eliminate errors, reduce paper processing, and increase the accuracy of inventory data. And with increased accuracy comes monetary benefits. One survey estimated that implementing barcodes into the world of payload integration would generate over $91,000 per year in recurring savings.

Unconventional barcoding

EV systems are not limited to 'hardware' tracking applications. Using a barcode system on paperwork can also increase productivity and reduce errors. An Automatic Identification system is being used in the Test Assembly and Inspection Record stations (TAIR) in the Orbiter Processing Facilities. The TAIR stations keep track of work that is being done according to Work Authorization Documents or WADs. WADs can be prepared for tile work, orbiter work, or even ground support equipment work. Each time a tasks is completed, the WAD must be logged in as finished and then prepared for the QDC or Quality Data Center to be archived. Depending on the position of the orbiter in the flow, the TAIR station can receive as many as thirty or forty documents a day to close out. Previously, this has been done by manually reading through the stack of documents, recording the WAD number, and alphabetizing the list according to system. At the end of the day this was a two hour job that nobody wanted. By assigning each WAD a barcode that would pull up all the information associated with that document and printing a cover page, much of this hassle was avoided. To scan in forty documents with a barcode wand takes about five minutes, and the computer automatically sorts the numbers and prints out a listing. When QDC picks up the documents they can simply scan the barcodes to verify the list with a portable scanner and then download that information into their computer record system back at the office. This saves time, eliminates errors, and decreases the number of times the information has to be manually entered into the computer.

Barcodes are also being used in the TAIR stations to replace the manual entry of repetitive information. When creating the WAD cover sheet, information must be entered to identify the type of work, location, and date, as well as other information. Barcodes are being used instead of the keyboard to shorten processing time and again reduce human errors. For instance, many of the WADs that go through a TAIR station will have an identification code that tells which OPF Bay the work is being done in and which orbiter and flight number is receiving the work. So a sheet of barcodes has been created that allows the user to simply scan a barcode in place of typing the information. The information contained in the barcode is translated directly into ASCII, (just as it is from the keyboard), fills in appropriate fields, and advances the cursor to the next line requiring input.

Another possible use for barcodes in the TAIR station is the charge out record. Efforts are being made to replace the handwritten sign out sheet with an EV system that will electronically assign responsibility to the technician picking up the WAD. Not only will this provide a more legible record it will also track the time spent in each phase of the repair. This should aid in streamlining work procedures and reducing bottlenecks.

Investigating new technology

The current technology used at KSC has many applications that are being taken advantage of, and there are other possibilities that make the barcode system a tool that will provide benefits well into the future. There are, however, some limitations to the barcode symbology. And while many of these limitations can be reduced or eliminated through the computer programming and software, there is still room for improvement. That is where the next generation of EV will take over. This new technology is two dimensional Compressed Symbology or CS. CS simply expands on the idea of the barcode. It still uses a machine readable code and corresponding software to process the received data, but it takes advantage of new ideas and advancements in technology.

Vericodes are currently the most prominent form of two dimensional symbols available. Two dimensional coding systems were first introduced in the form of tiered or layered barcodes by INTERMEC back in 1987, called Code 49. Other, similar coding systems soon followed. These included Code-a-Block, PDF 417, and 16K. While these forerunners of two dimensional technology were important to the development of the basic foundation, Vericodes are currently at the peak of this evolution.

Vericodes were created by Veritec, a California based company that was started when Robert Anselmo patented his ideas for the system in May of 1990. A Vericode is described as a symbol that includes a square array of data cells surrounded by a border of orientation and timing cells. Information related to the encoded data is contained within the square, while timing and orientation information about the actual symbol, is found along on the edges of the square.

Sample Vericode **(Average size)**

Vericodes use Charge Coupled Devices (CCD) to scan and decode the symbols. The CCD's look more like a high resolution camera, but the principle behind the technology is similar to that used on barcodes, specifically reflection scanning.

It is the versatility of the Vericode that brings it to the cutting edge of innovation. It's capacity is greater, it's durability is better, its accuracy is improved and the Vericode is an actual compressed symbology. It uses mathematical algorithms to convert streams of data into coded patterns. Therefore, there is not the one-to-one mapping of character to symbol that is found with conventional barcodes. This allows for a greater amount of information to be stored in the same amount of space. In fact, the capacity of the Vericode is nearing one hundred times that of a barcode. The average Vericode is 3/8 inch square and contains anywhere from 20 to 50 characters. In comparison the average barcode is approximately 3/8 X 1 inch and contains 5 to 9 characters. Microvericodes have also been developed that are as small as four microns (4/10,000 of a meter), which can be decoded using a microscope. Using ultra high density data compression these symbols can still contain up to 16 characters.

Another advantage of Vericodes is their durability. This is not only a reflection of the various marking methods developed for the symbol, but also an indication of the error checking and redundancy built into the system. Vericodes can be damaged or missing up to 50% of the symbol, and through the use of the algorithms and built in redundancy, still recover the encoded data.

Speed and accuracy are not lost due to this improvement in size and capacity. The accuracy of the system can be set to the limits desired by the user. Currently the error rate is set arbitrarily at one per seven million. During lab tests, a Vericode system successfully decoded four million symbols without error. This test was repeated with similar results. This would correspond to approximately 635 million bits of data. The speed of this process can be set to decode up to 60 symbols per second.

Another advantage of the Vericode is that it can be decoded regardless of it's orientation. The outer edge of the square contains information that provide the capability for 360 degree readability. This information could also be used to determine the orientation of the part the Vericode labels. Such a property could have applications in the manufacturing and assembly industry where alignment and orientation are critical.

With the variety of advantages that are available through the use of compressed symbology, the limits are only that of finding beneficial applications and utilization of this technology.

And while there are many benefits to the Vericode system, there are also drawbacks which must be examined before barcodes are completely abandoned. One of which is that there are real-time considerations when dealing with a new system. The idea to implement the barcode system began back in 1982 and has yet to achieve completion. The ability to change things overnight does not occur just because of a breakthrough in technology. The incorporation of the Vericode will take time even if it is deemed necessary and extremely beneficial. Another consideration is that of compatibility. Currently, the barcode systems do not have the capability to read Vericodes, and it would be hard to phase in a Vericode system. Money is of course another factor not to be overlooked. Cutting edge technology is never inexpensive, especially when the project is as far reaching as that of the space industry. The availability of the product is limited solely to Veritec and that would be a single point of failure in the system.

Conclusion

Electronic Verification does have potential and the space industry needs to take full advantage of the opportunities available with it, but we must also be reasonable in our approach. Electronic Verification as a whole has provided us with many benefits and savings as well as the ability to see new possibilities. We need to continue to work toward finishing the project started 14 years ago, but not dismiss upcoming ideas because of complications. We need to continue to consider new applications for the current resources and think of ways to incorporate new technology into both prevailing and upcoming systems. As long as we continue to think, apply, and strive for efficiency, we will continue to grow, improve, and succeed.

STORAGE INFORMATION MANAGEMENT SYSTEM (SIMS) SPACEFLIGHT HARDWARE WAREHOUSING AT GODDARD SPACE FLIGHT CENTER

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Abstract

Goddard Space Flight Center (GSFC) on site and leased warehouses contain thousands of items of Ground Support Equipment (GSE) and flight hardware including spacecraft, scaffolding, computer racks, stands, holding fixtures, test equipment, spares, etc. The control of these warehouses, and the management, accountability, and control of the items within them, is accomplished by the Logistics Management Division, Code 230. To facilitate this management and tracking effort, the Logistics and Transportation Management Branch, Code 234, is developing a system to provide warehouse personnel, property owners, and managers with storage and inventory information. This paper will describe that PC-based system and address how it will improve GSFC warehouse and storage management.

Introduction

At any given time there may be a dozen or so space projects in various stages of development at NASA's Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. COBE, EUVE, BBXRT, HST, GEOTAIL, GGS, GOES, SPARTAN, SHOOT, EOS, GRO, TRMM, XTE, are just a sampling of the acronyms and abbreviations that make up the alphabet soup of project names at GSFC. Each of these projects has varying amounts of space flight hardware, flight support equipment, and ground support equipment that is used for fabrication, manufacture, assembly, test & integration, launch support, or operations. When this equipment is not in use, it must be stored. The HST project alone requires approximately 22,000 square feet of storage space for GSE and hardware. After the launch of a project, equipment is placed into storage for a myriad of reasons. These include reuse on the same project, reutilization by another project, or use for a servicing or repair effort. The equipment may also be declared excess to be screened for utilization by other agencies. In order to effectively manage a storage program, records must be maintained that can, as a minimum, identify the item and its location in the warehouse. Additional information such as the owner, the owner's phone number, physical dimensions of the equipment, when it was placed into storage, expected duration of storage term, special environmental and/or handling requirements, etc., is also needed by the warehouse manager. As the quantity and complexity of information increases, it becomes readily apparent that an automated system for managing and manipulating the data and preparing reports becomes an asset, if not a necessity. To more effectively manage the warehouses and the assets they contain, logisticians of the Logistics Management Division/Code 234, sought data base management system that could be adapted to their needs. When an existing system could not be readily identified, they set out to develop their own. As a result, SIMS has been developed and is now undergoing system test and refinement at GSFC.

General Requirements

Code 234 desired that the system be inexpensive to develop due to the budget constraints that affect most government agencies. They also wanted a PC-based system to preclude the need for exotic or expensive special-purpose hardware or software. The GSFC Local Area Network (LAN) was to be used to provide multiple workstation access to the system for simultaneous use from both contiguous and remote locations. Although the system was to be developed and used primarily by Code 234, it would have the potential to be used by the flight projects and other organizations for inventory control of their hardware. To ease the burden of the user, the ability to expand the system to use a full-feature bar code capability was required. Also, the software had to be fully expandable to meet future requirements such as being able to interface with optical disk storage and imaging. Imaging was desired to enable users to have a ready display of the items in storage especially for identifying potential for utilization by more than one project. It was envisioned that this data base system was to be the first of a series of applications to ease the burden of inventory control at GSFC for both capital and non-capital equipment.

Inventory Control

SIMS was developed to be a menu-driven inventory control package that could provide rapid information on the status of inventories, the location of items, and a history of 2transactions. Controls within the software allow the users to perform inventory tracking and control by project, transfers, and inventory maintenance. Code 234 dictated the following functions as necessary to SIMS:

- Project Equipment Receipt
- Transfer
- Inventory/Location Maintenance
- Equipment History
- Tables
- Reports and Forms
- Batch Updates with Verification
- Forms Generation
- File Import/Export Capability
- Bar Code Scanning
- Graphic Imaging
- Interface with other property control systems (NEMS, NPDMS)

Equipment Receipt

The Equipment Receipt function is derived from a listing or importable database of equipment to be entered into the inventory. This listing is provided by projects or organizations which own the equipment. The listing is used to process and verify receipts and to forecast space requirements for utilization and planning. SIMS has the capability to check records for duplication during manual entry or import of data from a list. Once the item has been entered into the system, the system automatically flags available storage locations that fit the parameters and criteria entered into the record. When the record is completed and saved, the item quantities are entered as received and automatically added to the update buffer for appending to the main inventory file.

Transfers

The Transfer File contains records with information on the movement of equipment for the following conditions:

- From one GSFC location to another
- From one bin to another
- From container to clean room and/or back into storage

If an item is removed from the inventory because it has been excessed, incorporated into a product, returned to the supplier/producer, or is withdrawn from inventory for any other reason.

The Transfer File provides most of the data for a History File and it includes all fields necessary to indicate a new location, transfer date, transfer document, new responsible party, etc., and must automatically append to the History File whenever a transfer is entered. When equipment ownership changes, SIMS will globally replace organization code or other unique fields related to ownership. SIMS will also globally replace locations for any set of items.

Inventory/Location Maintenance

The Inventory Maintenance File provides access to defined tracking tools and includes the following specific capabilities:

Project Inventory by Project - The historical file of active/closed projects accessed through a pop up screen or by manually entering the project number.

Current Inventory Status - Provides the current inventory by project and/or location, with automatic flags if schedule review action is required.

Space Utilization and Projections - Provides graphic and tabular records of storage space utilization, and provides forecasts of space needs derived from project requirements defined in the Project Equipment Receipt records.

Periodic, regular Transaction Reports by Project and/or Location - Provides the basis for periodic activity reporting.

SIMS includes an Interactive Locator System to assist in the warehousing and management of inventory by selecting and displaying tabular listings of available storage locations. The storage location dimensions for each storage facility and grid locations within the storage facility are entered into the system. Information such as physical description (e.g., 2nd tier or drawer #6) and load limits of bin/storage areas are also entered into the system. Available bins/storage areas are selected against information entered into the database for individual inventory items. In usage, for example, the weight and dimensions of an inventory item would be entered along with relevant environmental requirements such as temperature, humidity, etc., The system would search all available storage locations and bins, and list those locations that match the required parameters. In addition, using data entered into the database for inventory items, the system will generate space utilization and forecasting reports for use in managing existing warehouse space and planning for future storage needs. NASA-defined tracking requirements are built into the system design. Any field or combination of fields in the database can be queried for information on the inventory and its movement. This includes capability for tracking/verification, down to and including the level of detail necessary for the verification that equipment has been loaded onto a vehicle for delivery, and (as a next step) then delivered. The system is capable of matches and near matches, sorting in order by closest match, and indicating where exact matches do not occur.

Equipment History

The software maintains a historical record of all record changes for each item of equipment. This history is displayable on request either as a movable window over the record display or as a full-screen display which may be scrolled as necessary. An item report can also be formatted providing the main record information of a particular item and its chronological history. The history files are a permanent part of the record and are updated automatically whenever the data base is updated and the update buffer is cleared. Data can be entered directly into the history database and edited without accessing the property record. History data can be entered in random order and will always be displayed in chronological order.

Tables

Tables are available for access through pop-ups and windows to provide rapid lockup capability for the following database fields:

Location Table - Relates location bar codes to clean rooms/containers/warehouses/bins.

Project Table - Provides information on GSFC projects including data such as project name, location, responsible person, phone number, inventory locations, and assigned project assembly location.

Manufacturer Table - Contains Manufacturer Codes (CAGE) as referenced in Defense Logistics Agency Cataloging Handbook.

Unit of Measure Table - Contains unit of measure information expressed as a two-character alphabetic code that denotes a recognizable physical measurement (length, weight, volume) or count of an item (foot, gallon, pound, each).

Environmental Code Table - Contains specific conditions (i.e., temperature, humidity, purge, cleanliness, packaging, inspection) under which an item is handled, stored, or maintained.

Hazard Class Table - Contains hazard related categories based on NASA requirements.

Storage Location - Contains information related to NASA utilized storage sites.

Status - Contains NASA developed and approved status codes and descriptors.

Condition - Contains condition codes and descriptors.

Transfer Types - Contains codes and descriptors for type of transfer categories (i.e., Shipped to another location, moved to another bin, final disposition, declared excess, etc.)

Document Type - Contains information on authorizing document types.

Address Table - Shipping address.

Security Table - List of authorized signature/ approval codes. This table is accessible to users and is maintained by the GSFC Designated System Supervisor.

SIMS software accommodates at least 20 additional user-defined tables without software modification. SIMS provides for rapid marking of data ranges within tables allowing direct entry into the database utilizing the mouse.

Reports and Forms

SIMS has a very flexible report generation capability, reporting to screen, disk, or to choices of at least ten common laser and matrix printers. Reports include inventory status, stock location, monthly operations reports, etc.,and has a menu-driven capability to produce ad hoc reports for any of the records. Searches can be accomplished using variables such as project code, receipt or issue dates, location, etc., and report to screen, disk, or printer. The system can also generate forms. The forms which have been scanned are available on screen for the operator to fill out and print. Logistics forms such as shipping documents, storage requests, etc. can be produced automatically, retrieving applicable fields from the database records. The security levels within SIMS allow users to electronically approve their requests, thus eliminating the need to send the form to the Storage Manager and cause undue delays in processing requests. SIMS can also produce property labels including bar codes for property identification and control.

Summary

Initial SIMS development is completed, and the system is presently undergoing test, evaluation and debugging by Code 230 Logistics Management Division personnel at GSFC. A data entry clerk has transferred existing storage data into the system and has completed the on-screen forms for new storage requests. SIMS users will have Local Area Network (LAN) access to SIMS, and the requirement for hard copy paperwork will be eliminated. It is anticipated that SIMS will greatly facilitate the storage operations and inventory control of project hardware and equipment at GSFC. The inherent flexibility of the system will enable the government to expand its capabilities as the need demands.

BIOGRAPHIES

Ms. Lindy Bingham is the Manager of the Space Flight Hardware Storage Program at NASA/Goddard Space Flight Center. She has been assigned to Code 234, Logistics and Transportation Management Branch, for the past 10 years. As the Storage Manager she oversees the operation of on-site government warehouses and off-site warehouses leased by the Code 234 support contractor. She plays a major role in the preparation and execution of PHST Plans for major projects and programs at Goddard. Ms. Bingham has received numerous awards and recognition for her achievements in the management of the GSFC storage program.

Dick Kubicko, CPL, is a senior member of SOLE and has over 25 years experience in logistically supporting NASA and USAF space systems. He is an Integrated Logistics Support (ILS) Engineer for the logistics support contractor to the Logistics Management Division/Code 230, at Goddard Space Flight Center (GSFC), Greenbelt, Maryland. Over the last 5 years, Dick has planned, executed, and provided logistics support for most of GSFC's major space flight projects, including the Hubble Space Telescope Project. He has a B.S. degree in Engineering and a M.S. in Logistics.

SUSTAINING SPACE SYSTEMS for STRATEGIC AND THEATER OPERATIONS A Study Perspective

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ABSTRACT

Our Desert Storm experience in the tactical utility of DoD space vehicles demonstrated that DoD's investment in space technology can provide a significant military advantage during times of crisis and war. The satellites what gave us such marvelous intelligence in locating, tracking, and enabling the successful attack of key targets resulted in a spectacular military success. However, without an on-orbit servicing capability, the fuel consumed to maneuver these satellites into position over the battlefield shortened their useful life by as much as two years. During the 1970's and 1980's, the Air Force aggressively pursued an or-orbit support capability to support and maintain it's space-based assets. However, in the early 1990's, budgetary and political priorities canceled the programs that would have made this a reality. Realizing that a future decision may be made to reinvestigate on-orbit support, the United States Space Command (USSPACECOM) sponsored a study to document efforts undertaken by the Air Force during the 1970's and 1980's in developing strategies and actions to achieve certain tenets of on-orbit support. The study represents an attempt to gather, review, summarize, and archive the most important research performed during this period. It will serve as a historical perspective upon which to base future research and development activities. This paper presents an overview of that study.[1]

INTRODUCTION

From the 1960's through the 1980's, on-orbit support concepts and analytical tools were developed by National Aeronautics and Space Administration (NASA) and DoD to access and evaluate the potential for on-orbit servicing of space systems. Many studies were performed to assess the technical feasibility and cost effectiveness of accomplishing satellite maintenance and servicing operations in space.

In general, these studies concluded that on-orbit maintenance and servicing is technically feasible and that no technology breakthroughs are required. Depending on constellation size, location, and on-orbit support concept utilized in the analysis, these studies demonstrated a potential life cycle cost savings range of 10 to 50 percent through the employment of an or-obit support strategy.

With the cancellation of the Orbital Maneuvering Vehicle (OMV) and the Satellite Servicer System Flight Demonstration (SSS/FD) programs, the Air Force has not played an advocacy role or demonstrated an interest in developing an on-orbit support capability. NASA, on the other hand, has continued to develop an on-orbit support capability that was, again demonstrated during the Hubble Space Telescope (HST) repair mission.

BACKGROUND

The March 1992 update of Air Force Manual (AFM) 1-1, *Basic Aerospace Doctrine,* addresses the increasing role of space assets in supporting and sustaining space operations. The document states, in part, that sustained employment of space assets must be planned for to ensure sufficient replenishment of space-based resources is achievable when adapting to changes in circumstances dictated by mission operations. The doctrine clearly states that on-orbit support for space assets can be crucial to campaign success and that flexibility in space employment will require a combination of reserve platforms and launch systems, development of on-orbit spares, and the employment of both robotic and manned space platforms. Further, it cites that a space platform's effectiveness can be significantly expanded by providing vehicles and crews to repair or modify the platform, service it, or restock consumables such as fuel.

USSPACECOM's December 1990 Assured Mission Support Space Architecture (AMSSA) focused upon the follow key objectives: Robustness, flexibility, survivability, sustainability, availability, affordability, and normalization of support to space assets, and supportability of deployed space systems. To assure the United States has and retains ready access to space during peacetime and during times of increased global and regional tensions, the AMSSA study identified six specific initiatives, referred to as the "Big Six", that must be improved and/or implemented: Communications; Navigation; Launch Capability; Command and Control; Satellite Control; and Integrated Logistics Support of space systems. It is the latter that addresses several tenets of the on-orbit support doctrine contained in AFM 1-1.

FEASIBILITY OF ON-ORBIT SUPPORT

Since the 1950's, man has been launching and operating satellites in space. These spacecraft have had varied missions such as communications, navigational aids, experiments, weather, surveillance, and other military missions. The concept of on-orbit support dates from the first satellite failure. In the early days of space flight, the first concern was to merely get the satellite into orbit. Once that barrier was passed and orbiting satellites began returning data, interest turned toward increasing satellite performance. The strategy for maintenance of these spacecraft was reconfiguration by telemetry to correct individual element failures and abandonment after critical failure. Abandoned satellites are usually replaced with either a new satellite launched from the ground or a pre-positioned on-orbit replacement satellite. The concept of abandoning large and expensive satellites after failure is counterproductive in a time of reduced defense budgets.

During the 1980's, in partnership with private industry, NASA developed the Multimission Modular Spacecraft (MMS) design, a reusable bus containing three replaceable boxes that control spacecraft power, data handling, and attitude. Solar Max, launched on 14 February 1980, was the first satellite to use the new design. After nine months of operation fuses failed in the attitude control subsystem module, rendering four of its seven instruments useless and compromising operations of the remaining three. In April 1994, the Space Shuttle Challenger was launched on a mission to capture and repair Solar Max. Although many unexpected difficulties arose during this mission, Solar Max was restored to service and a new era in orbital servicing and repair was launched. This mission provided the experience and know how necessary to capture and launch into their proper orbits the Palapa-B and Westar-6 satellites later the same year. These satellites had been placed into a wrong orbit due to a failure in their booster stage. Also, during this period, NASA designed and built the Hubble Space Telescope (HST) specifically to be maintained on on-orbit by astronauts through extravehicular activity (EVA). Should the space station become a reality, it is intended to be maintained on-orbit through a combination of EVA and the use of sophisticated robotics.

By the end of the 1980's numerous DoD and NASA studies and design concepts resulted in the establishment of a clear requirement for an on-orbit support capability. As a result, NASA and the Strategic Defense Initiative Organization (SDIO) formed a partnership to develop a Satellite Servicer System Flight Demonstration (SSS/FD) program. This was a joint effort to initiate a program to design, develop, and demonstrate a satellite servicing capability. A series of three flight demonstrations scheduled for 1993 through 1995 was planned. During the same timeframe, SDIO formulated a Space Assets Support Systems (SASS) implementation plan based upon existing and near-term technologies and capabilities. The plan, essentially a preliminary acquisition program plan, recommended that a SASS system program office be established to manage the design, development, and deployment of the SASS. National political and budgetary considerations forced the premature cancellation of the SSS/FD program and eliminated an opportunity to develop and demonstrate a very feasible, cost-effective alternative to the expensive abandon and replace concept currently used when spacecraft encounter failures, critical anomalies, or even fuel shortages.

In addition to the satellites that were diverted from other strategic surveillance missions during Desert Storm, there are several communications satellites currently on-orbit that have drifted slightly out of their intended orbits. There is insufficient fuel remaining in these satellites to maneuver them back into the proper orbit for maximum utilization of their capabilities. The capability to refuel these satellites on-orbit would provide military commanders the flexibility to reposition satellites to meet theater contingency requirements without significantly affecting the lifetime of the satellite. Additionally, survivability of the spacecraft could also be enhanced by an assured refueling capability in extending the satellite's ability to perform elusive and evasive maneuvers to counter threats.

NASA and DoD currently cosponsor an active committee under the American Institute of Aeronautics and Aeronautics (AIAA) that is developing necessary standards with the assistance of industry that, if implemented on future space vehicles or during block upgrades to existing space systems, could quickly produce the design and employment of on-orbit refueling ports or receptacles aboard many space vehicles to facilitate the safe, on-orbit transfer of fuel.

CONCLUSIONS

Many studies have been conducted which identified potential cost savings and other benefits to be realized through on-orbit support of space systems. There are wide differences in the amount of savings projected, sometimes even for the same space system, and the method of measuring the savings. The differences are due to the varied methodologies, assumptions, parameters used by the organizations conducting the studies. In addition to the potential cost savings, these studies have demonstrated that on-orbit support provides service life extension through a refueling capability, the capability to infuse new technology through the replacement of orbital replaceable units, and the ability to upgrade a system to meet expanded threats, etc.

There does not appear to be any technological roadblock to on-orbit servicing. The driving technologies have been identified. An increased capability to service and maintain spacecraft on-orbit will continue to evolve through NASA efforts and independent research and development efforts of the aerospace industry.

All of the studies examined concluded that there are several support capability needs which are key to the success of assuring mission support, and that these needs require positive commitment from senior Air Force and DoD decision makers. Most notable of these are the normalization of support of DoD space systems, modularity and standardization in space vehicle design, expanding DoD organic support, and the pursuit of on-orbit servicing capabilities to enhance satellite endurance.

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TECHNOLOGY INTERDEPENDENCY ROADMAPS FOR SPACE OPERATIONS

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Abstract

The requirements for Space Technology are outlined in terms of NASA Strategic Plan. The national emphasis on economic revitalization is described along with the environmental changes needed for the new direction. Space Technology Interdependency (STI) is elaborated in terms of its impact on national priority on science, education, and economy. Some suggested approaches to strengthening STI are outlined. Finally, examples of Technology Roadmaps for Space Operations area are included to illustrate the value of STI for national cohesiveness and economic revitalization.

Introduction

The strategic approach to space technology development can be viewed as a set of interwound modules floating in the ocean of business environment (Figure 1). The vision, goals, objectives are formulated with customers and resources available in mind (Ref. 1). The business plan translates the detailed objectives into products and services. A critical part of the entire enterprise deals with identifying and implementing processes which provide the most efficient operation for the good health of the business. Marketing is an integral part of ascertaining the viability of the products and the requirements for new products.

The ultimate goal of the process is to enlarge the customer base and/or increase the satisfaction level of customers. The correct process utilizes surveys, interviews, and other types of evaluations from the customers to develop a continuous stream of actions which should be undertaken to modify the strategy to provide the customer with the quality product, at the lowest price, and in the shortest possible time. The entire process has to be adjusted according to the changes in the business environment. The environment includes the overall health of the national economy, crisis situations caused by natural or human-made factors, status of competition, technological innovations, and any large shift in the preference of the customers.

This customer-driven process is the essence of the overall concept behind the development of space technology and its transfer to space projects/programs and the industry for commercial applications. The customers are the NASA and DOD program offices and aerospace and non-aerospace industry. The environment to which overall strategies must be linked continues to change as it always has. According to the Electronic Industries Association, Washington, D.C., during the first half of 1994, a record $48 billion worth of electronic products were exported, up 16 percent from the same period in 1993; however, during the same period, imports of electronic goods rose 18 percent to $55.3 billion (Ref. 2). The products included are computers, peripherals, solid state devices, communications, electrochemical equipment, electron tubes, passive components, and consumer electronics. The national deficit and the balance of trade have made economic revitalization a key item for the USA. The Council on Competitiveness has shown that growth rates in real standard of living correlate strongly with the manufacturing productivity. For the period of 1972-1992, the US ranked sixth in the world in this comparison behind Japan, Italy, France, United Kingdom, and Canada Ref. 3).

The role of technology in economic revitalization is widely recognized by academic, government, and industry communities. Recent studies conducted by the US National Critical Technologies Panel have identified applied molecular biology, distributed computing and telecommunications, flexible integrated manufacturing, electricity supply and distribution, materials synthesis and processing, microelectronics and optoelectronics, pollution minimization and remediation, software, and transportation as the nine industrial sectors particularly technology intensive and economically significant (Ref. 4). Taken together, they represent major portions of the future growth of the US economy. In the recent past, US President William J. Clinton and Vice President Albert Gore, Jr., have issued two major policies titled, "Technology for America's Economic Growth, A New

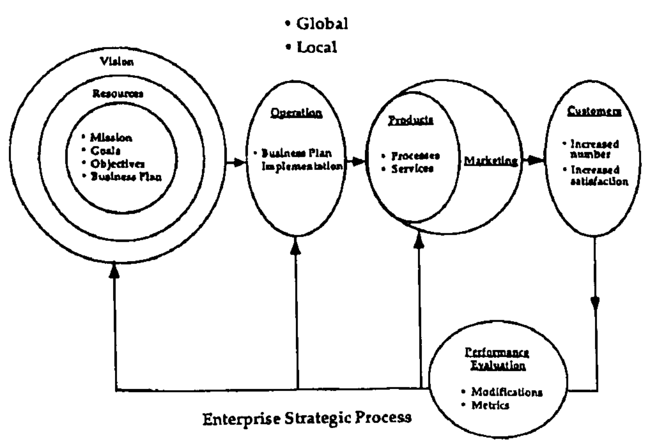

Fig. 1. Political Commercial Environment

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Direction to Build Economic Strength," and "Science in the National Interest" (Refs. 5,6).

The technology policy states that, "Technology is the engine of economic growth." Two-thirds of the productivity growth since this century's major depression can be attributed to technological advances. Thus, this policy states that, "Investing in technology is investing in America's future . . ."(Ref. 5).

The science policy draws its roots from President Clinton's November 23, 1993 statement, "This country must sustain world leadership in science, mathematics, and engineering if we are to meet the challenges of today... and of tomorrow" (Ref. 6). Another idea behind the science policy is from the statement of Vice President Gore at the Forum on Science in the National Interest, February 1994, "Science reveals new worlds to explore, and by implication, new opportunities to seize and new futures to create."

Three new directions discussed in these policy documents are: (1) coordinated management of technology all across the government, (2) forging a closer working partnership among industry, federal and state governments, workers, and universities, and (3) redirecting the focus of US national efforts toward technologies crucial to today's businesses and a growing economy. Laboratories managed by the Department of Energy, NASA, and the Department of Defense are being reviewed by the Administration with the aim of devoting at least 10-20 percent of their budgets to research and development (R&D) partnerships with industry. The overall environment is changing to gravitate highly toward technology partnerships for the economic revitalization which includes educational, research, manufacturing, and marketing aspects of newly developed products and services.

Space Technology Development

The vision of NASA has been expressed in various ways in the past three decades. Perhaps the most encompassing statement comes from the NASA Strategic Plan which was issued in May, 1994, and reads as follows: "NASA is an investment in America's future. As explorers, pioneers, and innovators, we boldly expand frontiers in air and space to inspire and serve America and to benefit the quality of life on earth" (Ref. 7). As a result of this vision , NASA has identified five strategic enterprises:

- Mission to Planet Earth
- Aeronautics
- Human Exploration and Development of Space
- Scientific Research
- Space Technology

NASA's Strategic Functions provide capabilities required by these enterprises. Specifically, these functions are (Ref. 7):

- Transportation to Space
- Space Communications
- Human Resources
- Physical Resources

The interplay of the strategies, functions, and customers is detailed in the NASA Strategic Plan. Figure 2 from this plan , shows this interconnectivity graphically.

The Aeronautics and Space Engineering Board (ASEB) Commission on Engineering and Technical Systems of the National Research Council (NRC) reviewed NASA's technology development for space science and issued a report in 1993. ASEB recommended eight technology areas with specific targets which are listed as follows (Ref. 8):

- Advanced propulsion
  - Advanced Earth-to-orbit engines
  - Reusable cryogenic orbital transfer vehicles
  - High-performance orbital transfer systems for sending humans to Mars
  - New spacecraft propulsion systems for solar system exploration
- Humans in space
  - Radiation protection
  - closed-cycle life support systems
  - Improved EVA equipment
  - Autonomous system and robotic augmentations for humans
  - Human factors research

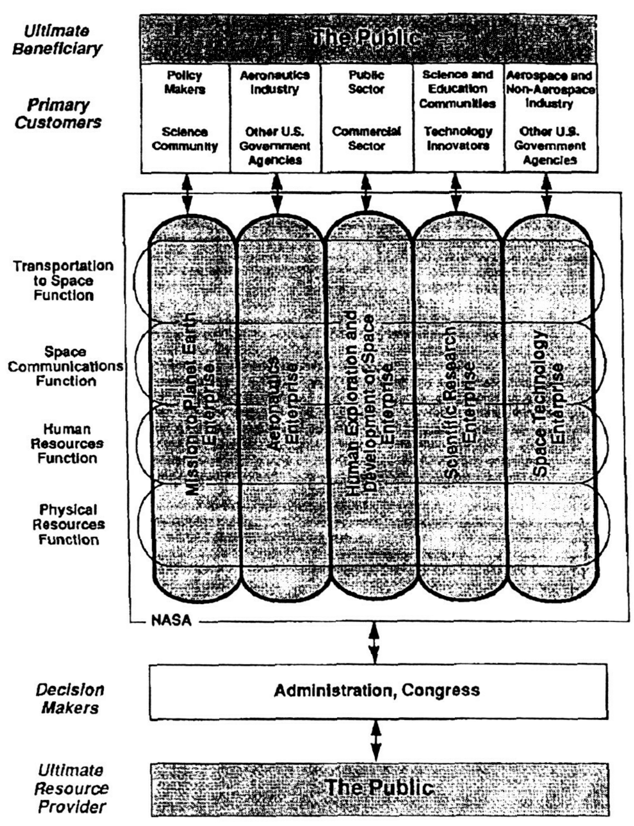

Fig. 2. The NASA Strategic Plan

- Autonomous systems and robotics
  - Lightweight, limber manipulators
  - Advanced sensing and control techniques
  - Teleoperators
- Space power supplies
  - 100 Kw nuclear power source
- Materials and structures
  - Advanced metallic materials based on alloy synthesis
  - "Hot" structures to counter reentry heating
  - "Trainable" control systems for large flexible structures
- Information and control
  - Autonomous on-board computing system
  - High-speed, low-error rate digital transmission over long distances
  - Voice/video communications
  - Spaceborne tracking and data relay
  - Equipment monitoring technology
  - Ground data handling, storage, distribution and analysis
- Advanced sensor technology
  - Large aperture optical and quasi-optical systems
  - Detection devices and systems
  - Cryogenic systems
  - In-situ analysis and sample return
- Supporting technologies
  - Radiation insensitive computational systems
  - High-precision attitude sensors and axis transfer systems

The Space Technology Enterprise has identified the following activities in support of the national needs (Ref. 9):

National Need	Space Technology Enterprise Activity
Fundamental Science	- Materials Research - Remote Sensing
National Security	- Advanced Space Transportation (AST) - Space Communications - Small Spacecraft Technology
Environmental Protection	- Remote Sensing - Small Spacecraft Technology
Industrial Competitiveness	- Space Processing - Commercial Network - Advanced Integrated Technology Program - Technology Reinvestment Program - AST
Space Exploration and Aeronautics	- Space Research and Technology

Flight experiments support each of the NASA Space Technology Enterprise Activities. In parallel with these, there is continued and new emphasis on space technology transfer programs including the Small Business Innovation Research (SBIR) program. The vision of the NASA Space Technology Enterprise (STE) is to pioneer with industry the development and use of space technologies to secure national economic competitiveness, to support space missions, and to provide low cost, highly operable access to space. The mission of STE is to stimulate the development and transfer of space technology to promote the creation of new knowledge, jobs, products and industries and their strategy is to maintain customer focus; provide space critical, world class capabilities; and leverage our resources. This includes inter-center collaborations, interagency collaborations, and private industry partnerships. Indeed, NASA offers unique opportunities for scientific research, technology development, and innovative methodologies for academic and research and technology institutions.

The space characterized by open space in terms of distance, voids, debris, gravity, electricity, magnetism, atmosphere, particles, temperature, acoustics, time, seismic activity, and electromagnetic radiation, provide a unique laboratory environment which can be economically used for experimentation and manufacturing of certain products. NASA's facilities and personnel offer a unique resource to other agencies, universities, and industry for developing partnerships. In addition, NASA has played an important role in the identification of new research areas and technology development needs because of its mission and objectives.

Many of the fundamental research and technology areas which have been identified by NASA as priority items continue to be special emphasis areas in the Department of Defense and several other agencies. This overlap in technology development is significant and needs to be addressed in overall national interest of avoiding duplication.

Space Technology Interdependence

The Space Technology Interdependency Group (STIG) was established in May, 1982 to identify and promote the pursuit of new opportunities for cooperative relationships between NASA and the US Air Force Systems command (AFSC).

In addition, STIG is chartered to monitor ongoing cooperative activities and identify areas of overlap and duplication. The Air Force responsibility now is located in the Materiel Command after the reorganization of the Air Force became effective in 1991. The goal of STIG is to provide advocacy, oversight, and guidance to facilitate and encourage cooperative development programs and to avoid duplication of effort and resources on space technology activities. Three categories of programs have been defined by STIG to characterize interaction The dependent program is the one in which a single set or subset of mutually constructed management, shared resources, and strong agency executive management support. An interdependent program is one in which some degree of overlap is stated in the agency program and/or technical goals, as outlined in a jointly developed program plan. It is assumed that there are complementary synergistic results beneficial to the participating agencies. Independent programs are conducted by one agency, with minimal or no cooperation from other agencies. In the past five years, US Army, US Navy, Department of Energy (DOE), Advanced Research Projects Agency (ARPA), Ballistic Missiles Defense Organization (BMDO), and National Oceanic and Atmospheric Administration (NOAA) have joined STIG.

The STIG was organized and is implemented by direction from a Steering Committee. The AF materiel Command Deputy Chief of Staff for Technology and the NASA Associate Administer for the Office of Space Access and Technology serve as Co-chairpersons and are responsible for designating members to the Steering Committee. The Steering Committee currently has members from the Army, Navy, BMDO, ARPA, and DOE. Steering committee members are from the Headquarters executive staff to provide technical expertise needed for direction and evaluation or programs.

The STIG program is implemented through eight technical committees. These committees are established by the Steering Committee (SC). The members are selected from participating field centers and laboratories. The co-chairpersons for the technical committees are nominated by members of the JSC and approved by SC co-chairpersons. We will briefly describe the implementation strategy for the STIG Operations Committee (SOC) to illustrate the organization and products that come from each of the STIG technical committees.

The SOC is co-chaired by Dr. Kumar Krishen of the NASA Johnson Space Center and Dr. Richard Miller of the USAF Armstrong laboratory. There are five subcommittees under SOC on the Robotics and Telepresence, Automation and Intelligent Systems, Human Factors, Life Sciences and Avionics. These five subcommittees are jointly co-chaired by technical experts from the two organizations, NASA and USAF. The membership of the SOC includes Army, Navy, DOE and BMDO in addition to NASA and the USAF. The SOC has 65 members. The members of SOC were nominated by their laboratories, research centers, or organizations and are approved by SOC co-chairpersons and the STIG Steering Committee. The SOC conducts two meetings on a yearly basis to: (1) review operations research and technology (R&T) plans, resources and progress within NASA, DOD, and DOE; (2) develop and maintain list and descriptions of current interdependent programs and encourage and recommend future interdependent programs; and (3) develop and review technology roadmaps for interagency projects. One key area of SOC work involves facilitating communication of R&T results in the operations area across agencies and various centers within these agencies involved in the operations R&T. This technical interchange is facilitated through STIG Operations, Applications and Research (SOAR) Symposium and Exhibition.

This author has participated in the STIG for a number of years. Furthermore, the author maintains very active interface with academia, industry, and R&T agency of the State of Texas. On the basis of many years of experience, the author proposes the following vision for Space Technology Interdependency (STI): "Create and promote STI infrastructures to encourage and coordinate cooperative projects in R&T for mutual benefits to the organizations involved." The benefits of STI are numerous and can be summarized as follows: (1) increasing interagency communications at all levels; (2) creating national technology cohesiveness through interaction with industry and academia; (3) sharing of expertise and facilities across agencies, industry, and educational institutions; (4) avoiding undesired duplication and reinventing through sharing of lessons learned; (5) developing cost-effective approaches through interdependent programs; (6) facilitating the identification of technology requirements for specific applications; and (7) creating an environment to gain a substantial edge in international competitiveness through technology transfer.

The STI management infrastructure should be easily implementable with a minimum impact to cooperating organizations. Furthermore, such a structure should be least affected by frequent reorganizations of the cooperating agencies/organizations. One such organization is proposed in Figure 3, and is patterned after the STIG discussed earlier in this paper.

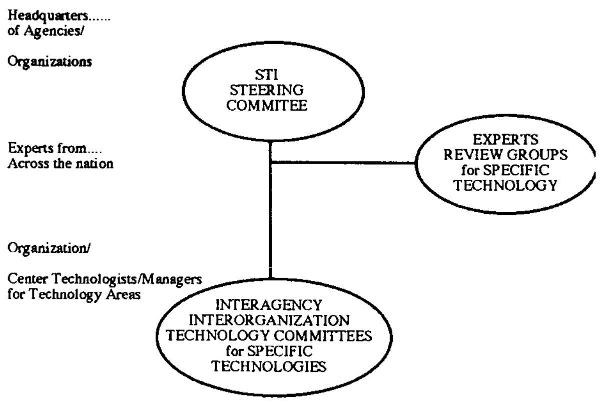

Figure 3 - Proposed STI Management Infrastructure

Operations Technology Roadmaps

As part of the Space Technology Interdependency Group (STIG) key activities, NASA and the Air Force are developing technology roadmaps aimed at providing a mechanism by which greater visibility and coordination can be achieved in U.S. interdepartmental activities and advances in the area of space technology development. These technology roadmaps are at a critical stage of development and will be a vital step to the implementation phase of technology transfer and future commercialization by private industry, as well as improving upon our own government operations. The roadmaps currently being developed and implemented are a coordinated effort of all the agencies involved in the space technology interdependency.

The SOC has compiled more than 20 roadmaps in its areas of responsibility. Typically a roadmap provides vision and objectives for a particular technology thrust. It identifies involvement of various agencies in research, design, development, demonstration, and flight experiment for the technology thrust. Key persons responsible for the interdependency management of various phases of development are identified. Estimated resources and schedule for the completion of the work are also provided. Details of anticipated milestones are provided along with a brief description of the goals to be achieved. These roadmaps are in their initial draft preparation stage. We are providing two such roadmaps in Figures 4,5 Robotic Exploration Vehicles and Human Workload Modeling.

It is crucial to emphasize that these roadmaps are being revised to reflect new budgetary data and are merely presented here to illustrate the usefulness such a resource for our National technology development. This author believes that such roadmaps should be revised on a yearly basis to accommodate new budgetary data and strategic emphasis. Furthermore, publication and distribution of such roadmaps can provide the catalytic effect for accelerating partnership by various organizations wanting to explore avenues of using interdependent efforts to achieve their goals. In the least, just to prepare these roadmaps and to review the achievements periodically will result in many government agencies and organizations getting together and, therefore, forging meaningful interdependencies.

Conclusions

The Space Technology Interdependency (STI) is a manageable task since space technology needs are relatively understood and there is a mechanism to periodically update the list of high priority space technologies (Ref. 10). The STI would facilitate identification of technology requirements with realistic specifications. The foremost requirement for the management structure for STI should be its ability to provide motivation to personnel to implement and promote cooperative efforts. Communications should be effective at all levels and decisions should incorporate both top-down and bottom-up inputs. There should be clear guidelines for measurement of success. The implementation of successful management infrastructure provides a challenge. It should be a process oriented and flexible approach. There should be emphasis on team work, and not on preconceived results. Most important, it should incorporate rewards and incentives for those who produce desirable results.

Acknowledgment

This work has been inspired by and received review from my colleague, Mr. Jerry C. Elliott, Assistant Chief Technologist, of NASA Johnson Space Center. He shares the same vision for STI.

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(5) Technology for America's Economic Growth, A New Direction to Build Economic Strength, President Clinton and Vice President Gore, Jr., issued by the White House, Washington, D.C., February 22, 1993.

(6) Science in the National Interest, President Clinton and Vice President Gore, Jr., issued by the White House, Washington, D.C., August, 1994.

(7) NASA Strategic Plan, issued by National Aeronautics and Space Administration, Washington, D.C., May, 1994.

(8) Improving NASA's Technology for Space Science, National Research Council Report, national Academy Press, Washington, D.C., 1993.

(9) Space Technology Enterprise, Office of Space Access & Technology (OAST), presented by Gregory Reck, Deputy Associate Administrator, OAST, at the Space Technology Interdependency Group Meeting at U.S. Air Force Phillips Laboratory, November 3-4, 1994.

(10) Krishen, K., Space Technology Requirements and Interdependency for National Competitiveness, Proceedings of the Thirtieth Space Congress, Cocoa Beach, Florida, April 27-30, 1993.

ROBOTIC EXPLORATION VEHICLES

VISION: To develop autonomous vehicles operating in harsh terrains and capable of reconnaisance, surveillance, data collection, and scientific experiments

OBJECTIVE: To augment soldiers in the field by enhancing autonomous search and destroy capability and to enable remote planetary exploration missions.

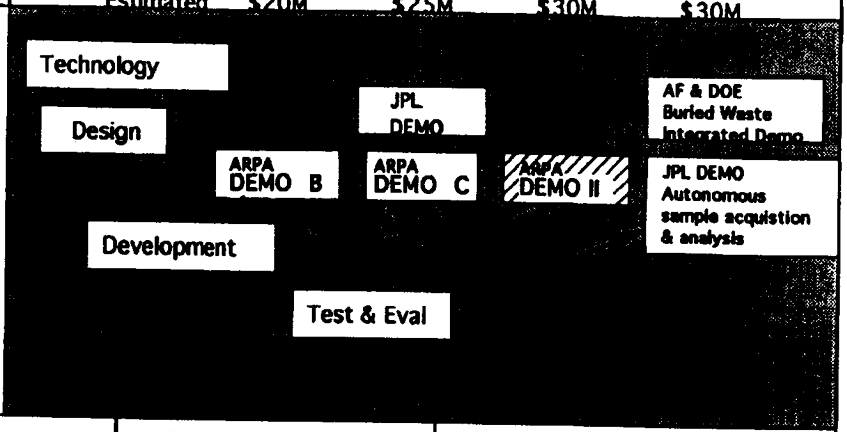
TECHNOLOGY AREA: Robotics & Telepresence

DISCIPLINE: Engineering

INVOLVEMENT

NASA	AF	ARMY	NAVY	ARPA	DOE
X	X	X	X	X	X
X	X	X		X	X
X		X		X	
X	X	X		X	X
X		X	X	X	X

	FY94	FY95	FY96	FY97
Estimated	$20M	$25M	$30M	$30M



DOD Key Personnel:

	AF	Army
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Joe Herndon, ORNL, DOE, 615/576-0119
Capt. Paul V. Whalen, USAF AL/CFBA, WPAFB 513/255-3671

NASA CENTERS: NASA CODE C/JPL

DOD/OTHER AGENCIES: ARPA, NAVY (EOD), DOE (ORNL, SANDIA), ARMY (TACOM), AF (AFMC)

FUTURE PLANS: Autonomous navigaton in unstructured environments, low-bandwidth communications and control, pattern recognition, miniature actuators, etc. Stereo vision from JPL developments will be used in ARPA Unmanned Ground Vehicle (UGV) project and by AF unexploded ordnance (UXO) clearance project.

ROBOTIC EXPLORATION VEHICLES

TECHNOLOGY GOAL: *To develop autonomous vehicles capable of operating in harsh terrains and capable of reconnaisance, surveillance, data collection, and scientific experiments.*

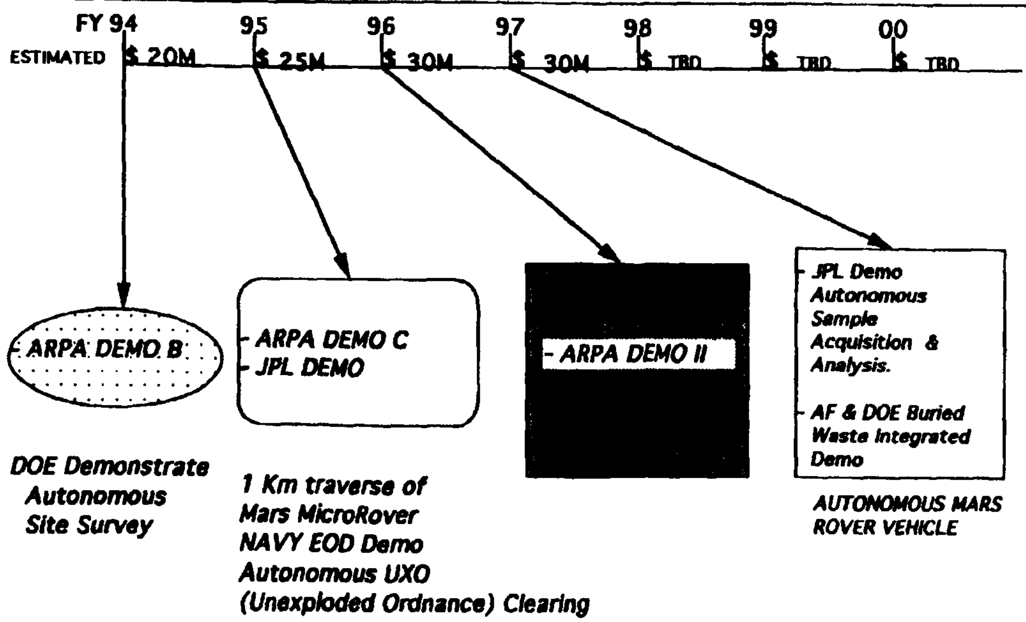


Fig. 4. Robotic Exploration Vehicles

HUMAN WORKLOAD MODELING

VISION: To contribute to the development of the scientific and technological foundations for safe and productive human presence in space.

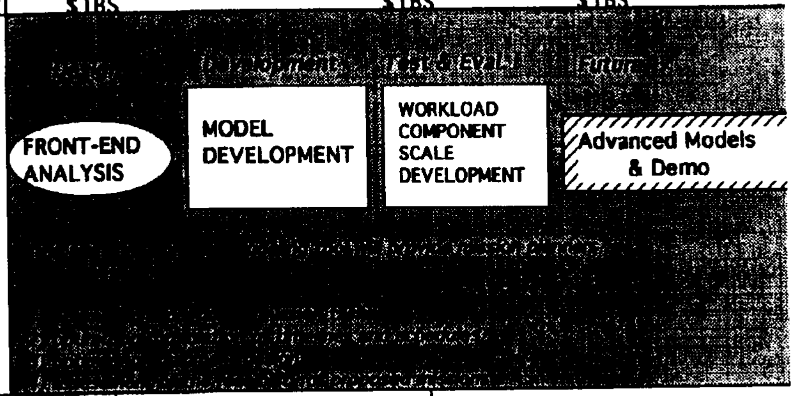
OBJECTIVE: To access the utility of task network modeling for studying: Function allocation strategies; effects of temporal, biological and environmental stressors on human performance; 0-g and partial-g effects on human performance; psychomotor, perceptual, & information-processing capabilities of the human operator; and effects of circadian and diurnal rhythms, sustained performance, and work-rest ratio, crew-coord. perform.

TECHNOLOGY AREA: Human Factors

DISCIPLINE: Life Sciences

INVOLVEMENT					
NASA	AF	ARMY	NAVY	ARPA	DOE
X	X				

FY95 $TBS → FY96 $TBS — FY97 $TBS



DOD Key Personnel:

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Address: Armstrong Laboratories/CFTO
Brooks AFB, TX 78235-5104
Phone: 210/536-3464

NASA Key Personnel:

MS. Barbara Woolford
NASA/JSC FCSD
Mail Code SP2, Houston, TX 77058
713/483-3701

Other:

None.

NASA CENTERS: NASA-Johnson Space Center/Flight Crew Support Division

DOD/OTHER AGENCIES: None.

FUTURE PLANS: The task network simulations developed will lead to a number of products that will be applied to future task networks simulations of the workload likely to be experienced during future missions. Specifically, the task network simulations will form the foundation for identifying overload conditions & developing strategies for reducing workload during space missions.

HUMAN WORKLOAD MODELING

TECHNOLOGY GOAL: To provide mission planners with a method for optimizing allocation of mission tasks; optimizing formulation of timelines, schedules and equipment design; and assessment of the feasibility of proposed missions.

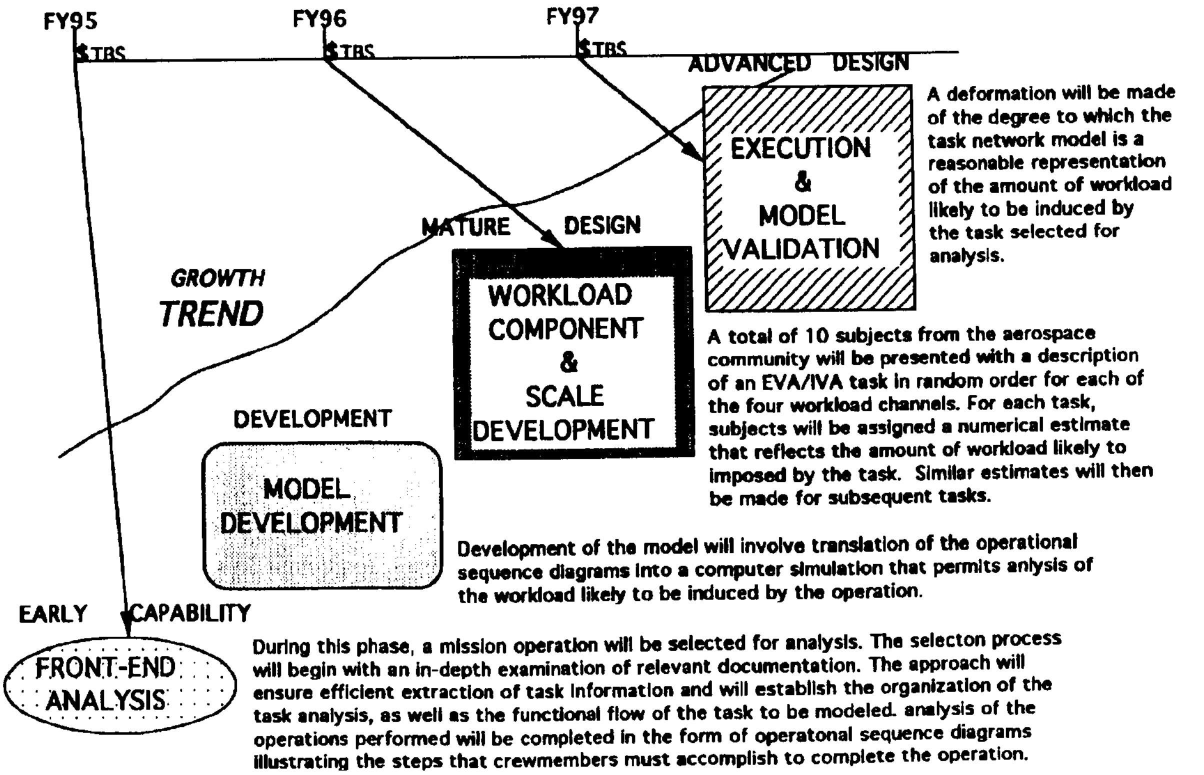

Fig. 5. Human Workload Modeling

Background

The Human Workload Analysis program of investigation is a joint effort between NASA/Johnson Space Center and Brooks AFB. The center of overall responsiblity for the implementation of the project is the Crew Interface and Analysis Section of the Flight Crew Support Division of NASA-JSC.

Major Milestones

USAF Cooperative/Human Workload Analysis Project is a 3-year, 4-phase program of investigation.

FY95 - Front-End Analysis
FY96 - Workload Component Scale Development
FY97 - Execution and Model Validation

Management Approach

The NASA-JSC principal Investigator, in conjunction with the Human Interfaces Department at Lockheed Engineering and Sciences Co. (LESC), supports the overall effort for JSC. The Principal Investigator will report directly to the Flight Crew Support Division. Under the direction of the NASA-JSC Technical Monitor, the Engineering Supervisor of the Human Factors and Ergonomics Laboratory (HFEL) and the human workload analysis lead will be responsible for completion of all deliverables.

Technical support is provided by Brooks AFB, Armstrong Laboratories, in the form of implementing the workload models in computer models. The Air Force provides expertise in workload modeling using SAINT, a network analysis tool This predicts workload on any of several channels. The AF has expertise in programming in SAINT, and takes the models developed by NASA and implements them. The programs are transmitted electronically to be run on NASA equipment.

The project is managed by the NASA technical manager, with Lt. Mitcha providing Air Force management of budget, manpower, and work as assigned by NASA. All funding comes from NASA's Office of Life and Microgravity Science and Applications, and funds are transferred to the Air Force to cover their efforts.

End Products/Users

The task network workload modeling tool currently under development will provide mission planners with a method for :

1) optimizing allocation of mission tasks,
2) optimizing formulation of timelines and schedules
3) optimizing equipment design, and
4) assessment of the feasibility of proposed missions

Major Deliverable And Periods Of Performance

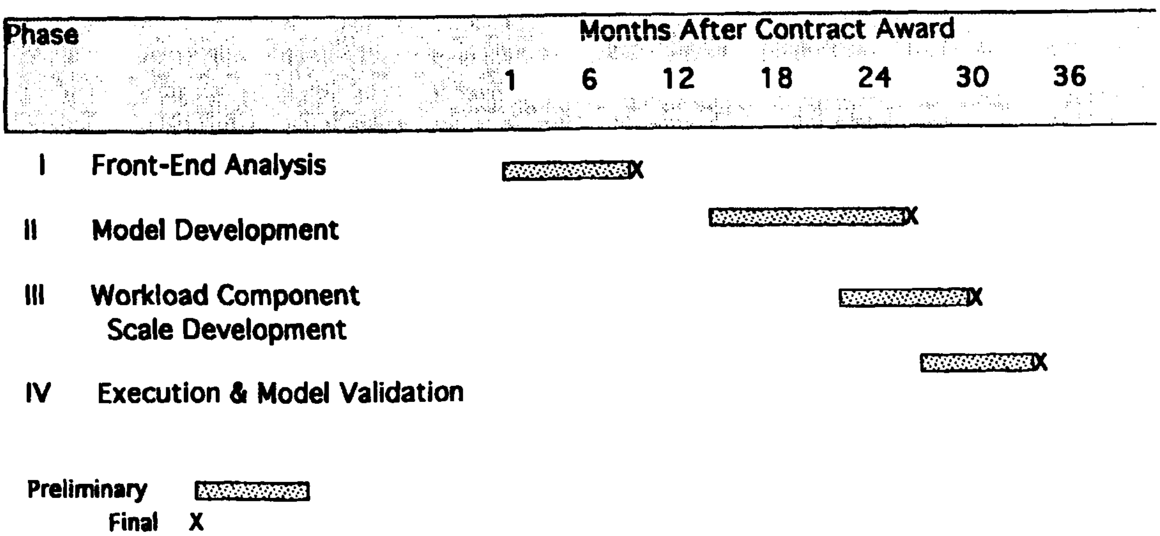

Fig. 5 (cont.). Human Workload Modeling

The Evolution of Mission Architectures for Human Lunar Exploration

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I. Abstract

Defining transportation architectures for the human exploration of the Moon is a complex task due to the multitude of mission scenarios available. The mission transportation architecture recently proposed for the First Lunar Outpost (FLO) was not designed from carefully *predetermined* mission requirements and goals, but *evolved* from an initial set of requirements, which were continually modified as studies revealed that some early assumptions were not optimal. This paper focuses on the mission architectures proposed for FLO and investigates how these transportation architectures evolved. A comparison of the strengths and weaknesses of the three distinct mission architectures are discussed, namely (1) Lunar Orbit Rendezvous, (2) staging from the Cislunar Libration Point, and (3) direct to the lunar surface. In addition, several new and revolutionary architectures are discussed.

II. Introduction

Since the inception of the space age, transportation nodes, such as parking orbits about the Earth and Moon, have been utilized to maximize mission planning flexibility while minimizing program risks. However, defining transportation architectures for the human exploration of the Moon is a complex task due to the multitude of mission scenarios available.

The mission transportation architecture currently baselined for the First Lunar Outpost (FLO), was not designed from carefully *predetermined* mission requirements and goals, but *evolved* from an initial set of requirements, which were continually modified as studies revealed that some early assumptions may not have been optimum. This paper will discuss the mission architectures currently under consideration for FLO and will investigate how these transportation architectures evolved.

There are three distinct mission architectures, (1) Lunar Orbit Rendezvous (LOR), (2) staging from the Cislunar Libration Point (CLP), and (3) direct to the lunar surface (Lunar Direct). These architectures are defined by how the vehicle(s) arrival at and departure from the Moon. Subsets of these three architectures are defined by whether the vehicle(s) depart from a space station and whether the crew returns to a space station, splashes down, or lands propulsively on the ground.

A literature search revealed literally hundreds of papers involving various aspects of these three architectures and their numerous subsets. However, only a few papers attempted to compare one architecture to another, and those only compared a few specific parameters. One study was found which compared all three architectures; but it was based on a specific set of predetermined assumptions, and was not formally published.

III. Background

On 25 May 1961, President Kennedy committed the United States to the goal of landing men on the Moon by the end of the decade. [1] That goal was achieved when Apollo 11 placed Americans on the Moon on 20 July 1969. [2] The United States performed five more successful missions to the Moon between 1969 and 1972, using a mission transportation architecture called Lunar Orbit Rendezvous or LOR. [1] Some useful Apollo statistics are listed in Table 1. Note that all were brief, near equatorial, front side missions, with surface stay times between two and three days.

Table 1: Apollo Landing Sites [4]

Apollo #	Date d/m/yr	Latitude	Longitude	Stay Time hr
11	7/20/69 (landing)	00° 41' 15" N	23° 26' 00" E	21
12	11/19/69 (landing)	03° 11' 51" S	23° 23' 08" W	31
14	1/31/71 (launch)	03° 40' 24" S	17° 27' 55" W	33.
15	7/26/71 (launch)	26° 06' 03" N	03° 39' 10" E	66
16	4/16/72 (launch)	08° 59' 29" S	15° 30' 52" E	71
17	12/7/72 (launch)	20° 09' 55" N	30° 45' 57" E	74

An overview of the LOR mission Architecture utilized by the Apollo missions is shown in Figure 2. Direct ascent from the ground to Low Earth Orbit (LEO) and Trans-Lunar Injection (TLI) were performed by a Saturn-5 rocket. The trajectories were designed to pass in front of the Moon, allowing the command module to perform the Lunar Orbit Insertion (LOI) burn on the back side of the Moon if all systems were performing well, placing the vehicle in Low Lunar Orbit (LLO).[1]

The vehicle consisted of two pressurized capsules, the command module, and the lander. The command module housed the crew of three on the outbound and return legs of the mission, and performed a hyperbolic direct reentry at the Earth, splashing down in the ocean. The lunar lander consisted of two stages. The first performed the de-orbit and descent burns, taking two astronauts to the surface, while the third astronaut remained in LLO with the command module. After a one to three day stay on the lunar surface, the upper portion of the lander performed the ascent burn and rendezvoused with the command module in LLO. The lower stage remained on the lunar surface, while the upper stage was expended in LLO, meaning it was left behind were its orbit would decay causing it to crash into the lunar surface.

On 20 July 1989, on the 20th anniversary of the Apollo 11 landing, President Bush challenged America to go, "back to the Moon, back to the future. And this time, back to stay." [2]

The NASA Administrator at that time, Richard H. Truly, quickly formed a task force to perform a three-month study of the human exploration of the Moon and Mars. [5] In November of 1989, the task force published the "Report of the 90-Day Study on Human Exploration of the Moon and Mars", [5] or the '90-Day Study' as it was dubbed. The majority of subsequent studies involving lunar exploration architectures evolved from this report.

IV. Evolution of Lunar Exploration Mission Architectures

The lunar mission architecture outlined in the '90-Day Study' was derived from the Apollo architecture, but included a number of important changes. Therefore, a summary of their findings and assumption is important.

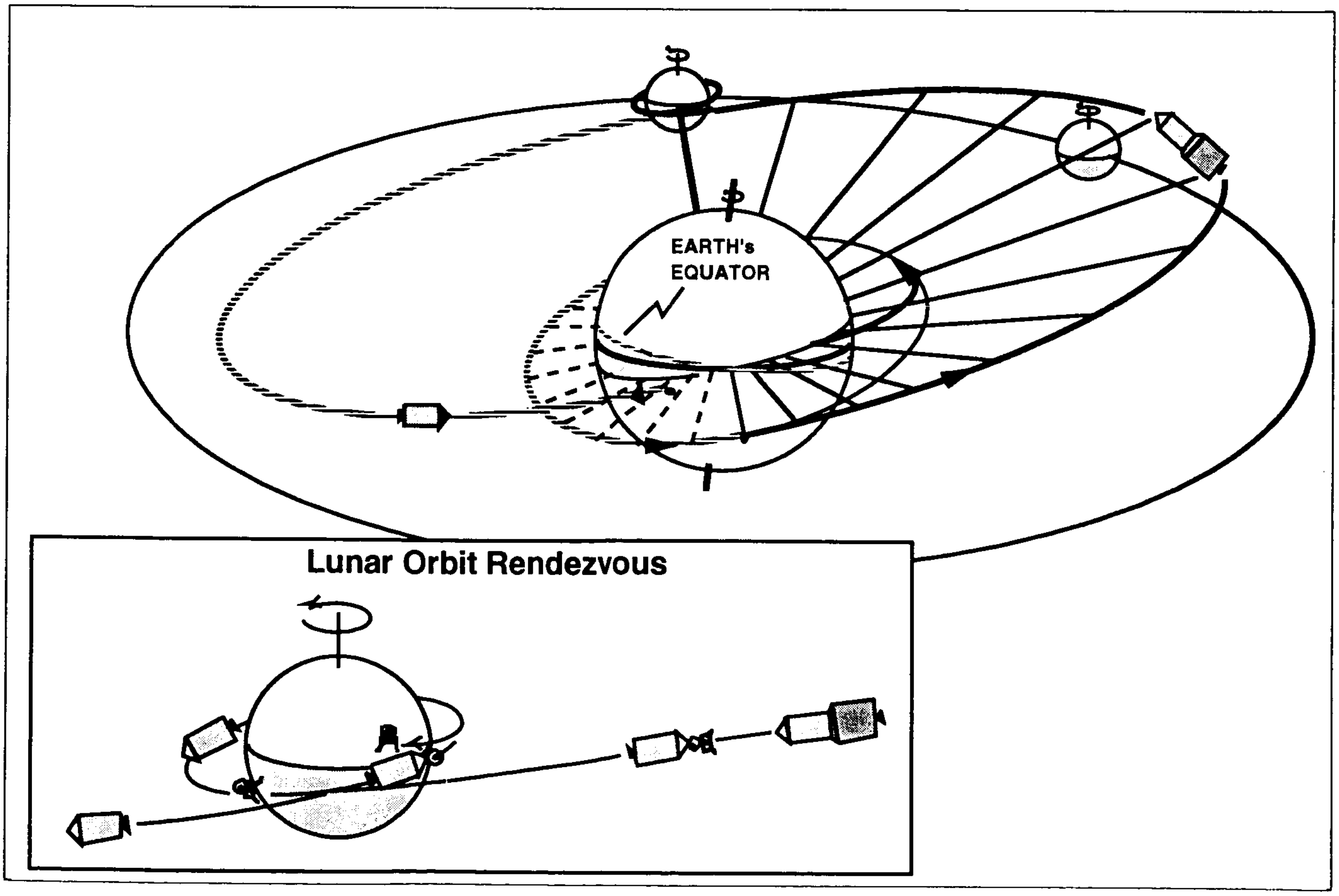


Fig. 2. Apollo LOR Mission Architecture

Summary of the 90-Day Study [5]

The team, faced with a short-term deadline, chose an overall architecture they knew would work, Lunar Orbit Rendezvous. However, the goal of the return to the Moon is to achieve a permanent presence there, which requires much longer stay-times, and thus a surface habitat and additional cargo. The initial habitat was required to support a 30-day stay. To achieve this, the team chose to split the mission into two parts, a cargo mission and a piloted mission. An autonomous cargo vehicle delivers a surface habitat and cargo to the lunar surface prior to the piloted mission.

The vehicle design consists of two pressurized modules as did Apollo, a Lunar Transfer Vehicle (LTV) and a Lunar Excursion Vehicle (LEV) (see Figure 3).

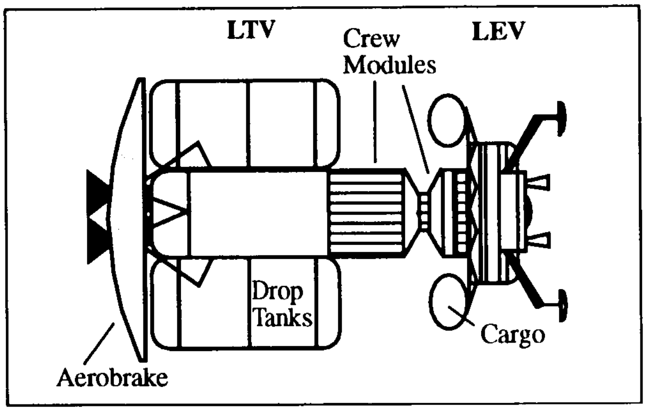


Fig. 3. '90 Day Study' Vehicle Configuration

The LTV is a *reusable* 'tug' that carries a crew of four and their cargo to the Moon and back, and transports the LEV to low lunar orbit. The assumed payload capability of the transfer vehicle is 33 metric tons or 16 tons plus the crew and excursion vehicle. The fuel chosen for the vehicles was liquid oxygen / liquid hydrogen.

The LEV is similar to the Apollo lander, an *expendable* two-stage lander. The first stage performs the descent to the lunar surface and is left behind. The second stage performs the ascent, rendezvous with the transfer vehicle, and is expended in LLO.

An additional departure from the Apollo architecture was the choice to assemble and launch the vehicle from Low Earth Orbit (LEO) near Space Station Freedom (SSF), rather than perform a direct ascent from the Earth's surface. Furthermore, a free-return trajectory was required for the piloted missions. An overview of this mission architecture is shown in Figure 4.

The mission begins with a translunar injection maneuver (TLI) performed by the LTV at a safe distance from the space station. A lunar orbit insertion (LOI) maneuver is performed upon arrival at the Moon. The LEV separates from the LTV and descends to the lunar surface with the crew and payload.

After a specified stay time, the Earth return leg of the mission is initiated with an ascent-rendezvous strategy designed to transport the crew and payload (if any) to the LTV waiting in lunar orbit. At this point, several options are available. The LEV can be brought

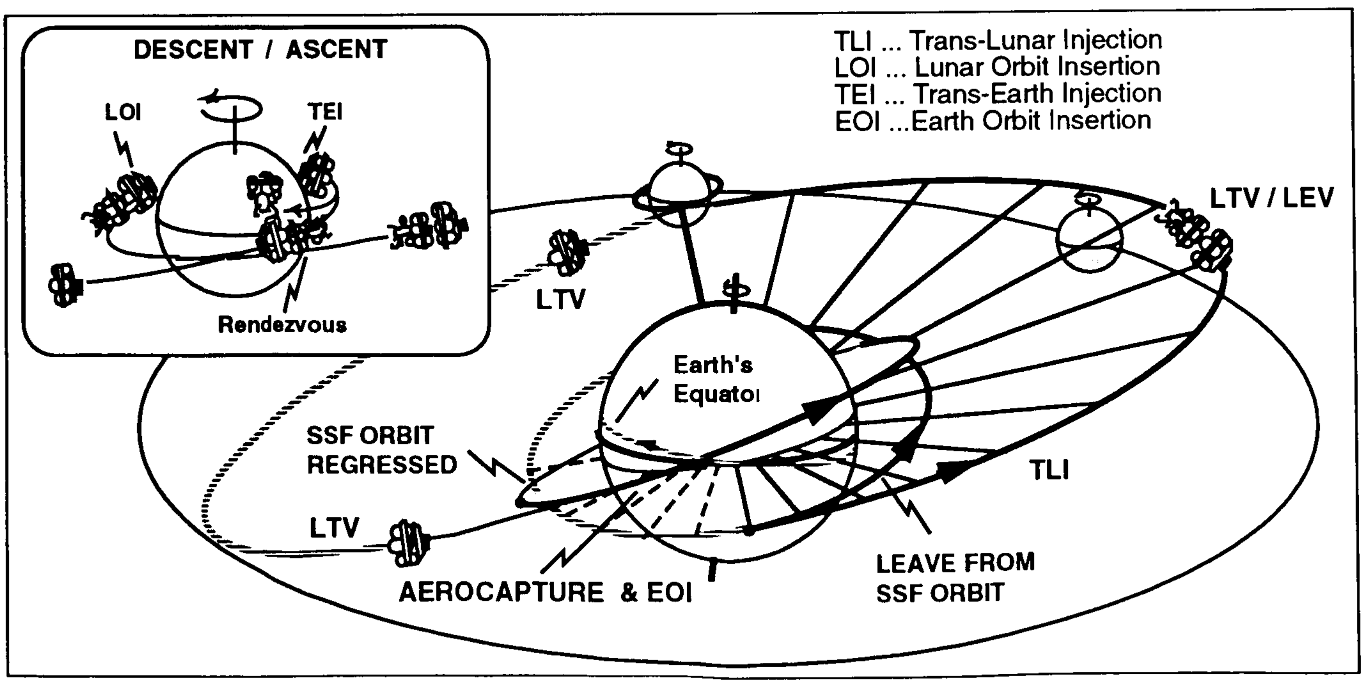


Fig. 4. '90-Day Study' Mission Architecture

back to the space station to be refurbished and reused. This option tends to significantly increase the initial mass in low Earth orbit (IMLEO) required to perform the mission. A second option is to leave the LEV in lunar orbit for reuse on the next mission. This increases mission planning complexity due to the additional rendezvous requirements placed on the following mission. In addition, long term stability of the lunar orbit is a non-trivial issue due to the complex selenopotential effects. This option also restricts landing site accessibility to those latitudes which are below the inclination of the LEV's orbit. A third option also enables LEV reusability but requires an in situ propellant infrastructure on the lunar surface. This requires storing the LEV on the lunar surface and taking advantage of lunar oxygen to reduce propellant transportation requirements from Earth. While an attractive option if lunar oxygen can be produced efficiently, it was not considered in this study due to the a priori requirements for a lunar base infrastructure. The fourth option utilizes an expendable LEV strategy, which has the effect of reducing both the initial mass in low earth orbit and the mission complexity, and was therefore chosen by the '90-Day' team. The LTV performs a transearth injection maneuver (TEI) which places it on an Earth return trajectory while leaving the expendable LEV in lunar orbit. An Earth aerocapture maneuver then places the LTV in an orbit whose apogee is ideally suited to a space station rendezvous. When the LTV is near apogee, a perigee raise maneuver, referred to as Earth orbit insertion (EOI), is performed. This maneuver places the LTV in a circular orbit compatible with the space station. The final rendezvous sequence completes the mission. The LTV and the aerocapture heat shield are refurbished at the space station for reuse on subsequent missions. [5]

Alternate Mission Modes

Following the '90-Day Study', numerous studies were performed to assess their design. Many of the studies unearthed problems with the assumed mission architecture. Some of the key problems are discussed below.

One of the first aspects of the '90-Day Study' architecture that was analyzed was the constraint of a free-return to the space station. Studies showed that opportunities for free return trajectories that would return the vehicle to the station are very rare, due to the complex geometry of the Earth-Moon system combined with a regressing station orbit. Opportunities during the eighteen-year lunar cycle occur at best once every few months, and in the worse years, are not available at all. Free-returns are available once every 6 to 10 days if the vehicle is not constrained to return to the station; however, free-returns are *only* available when targeting for *near-equatorial* lunar sites, regardless of where the vehicle departs from or returns to. [6] This was identified as a problem by a lunar site selection committee, which indicated global access is desired by the scientific community. [7]

Other studies showed that for non-equatorial missions, which must have higher inclination orbits, the orbits regress up to a degree per day. This, coupled with the rotation rate of the moon (about 13.2 degrees per day) can result in surface wait times of up to 14 days before the excursion vehicle can lift off to rendezvous with the transfer vehicle. In addition, high inclination orbits may only have minimum energy transfers available twice per month, and these opportunities may not coincide with the required alignment for a return to the regressing space station orbit. [8, 9]

As a result of these and other studies, two new mission architectures were identified as worthy of study, *lunar direct* and *high lunar staging.* [10]

Lunar Direct

Under the lunar direct transportation architecture, the entire vehicle descends to the lunar surface. No components remain in lunar orbit as opposed to the LOR architecture. This eliminates orbit rendezvous, simplifies mission planning, removes imposed surface stay times, allows global access, and requires the development of only one pressurized vehicle. However, the vehicle mass must be much higher than that of the LEV and LTV, since it must carry all of its Earth-return fuel down to the lunar surface and back. This mass increase corresponds to a larger IMLEO, which implies the need for either larger lift vehicles or more launches and assembly in LEO, when compared to the LOR architecture. In addition, the sensitivity of total vehicle mass to crew module mass limits the cargo capability of the lander, meaning it would be very expensive in terms of both mass and dollars to build a lander capable of staying a month or more at a time. Thus, an autonomously delivered surface habitat could be required, perhaps necessitating another launch. [10]

High Lunar Staging

The high lunar staging architecture is, in general, just a variation of lunar orbit rendezvous. By staging far from the Moon's gravity well, larger plane changes can be made with reasonable propellant use, allowing global access; something not feasible from low lunar orbit.

The payload capability is greater than that of the direct mode, but somewhat less than that of the LOR option. However, many of the phasing problems associated with the low LOR architecture apply to the high

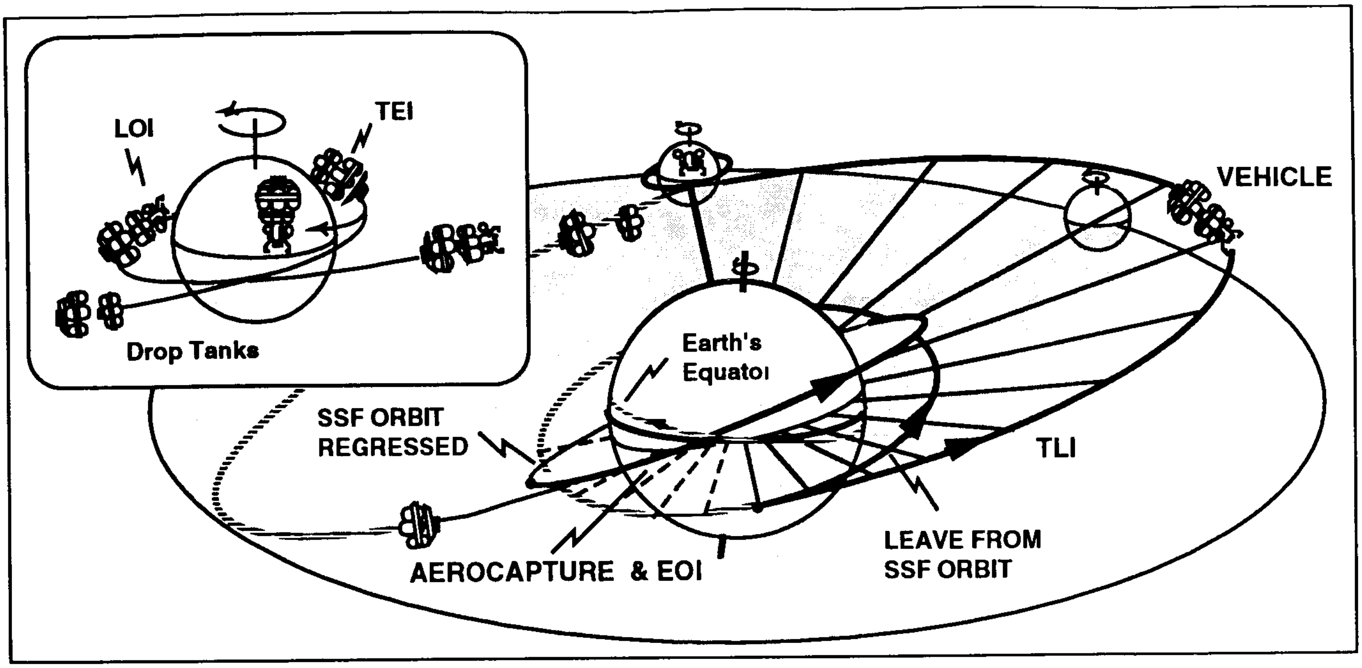


Fig. 5. Lunar Direct Mission Architecture

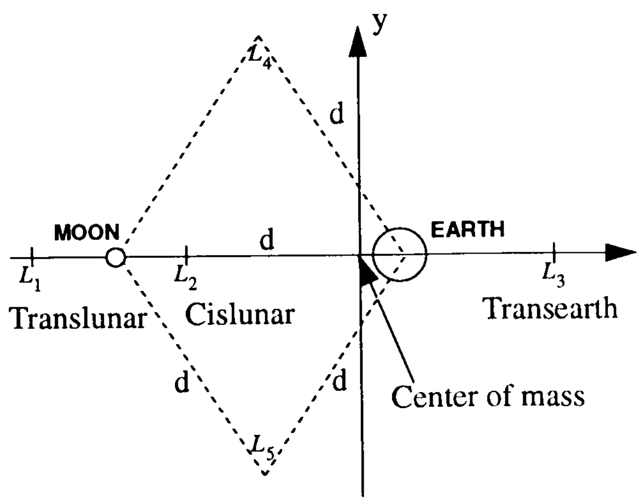
LOR as well. That is, with the exception of one special high-altitude staging point, the cislunar libration point. Staging from the cislunar libration point, alleviates many of the phasing problems associated with lunar orbit rendezvous, because it does not actually orbit *about* the moon, but remains *fixed* above the lunar surface, at a point between the Earth and Moon. [10]

The cislunar libration point (CLP) staging scenario allows for a smaller lander than the direct mode, while providing moderate payload capability with a lower initial mass in LEO. It allows global access and a return any time from the surface. In addition, free returns on the outbound transfer are always available. [8]

Cislunar Libration Point Staging

Libration point locations are found as special solutions of the restricted three-body problem which is defined as follows: two mass points m_1 and m_2 of arbitrary finite mass revolve in circular orbits about their center of mass under the influence of their mutual gravitational attraction. A third body (m_3) of infinitesimal mass (that is it does not influence the motion of the primaries m_1 and m_2) moves under the gravitational influence of the primaries. The "problem" is to describe the motion of m_3 , which is not required to move in the plane of motion of the primaries. All motion takes place in a rotating cartesian system whose origin is the center of mass. The x-axis is along the line connecting m_1 and m_2 and the z-axis is normal to the plane of motion of m_1 and m_2. For this analysis, the larger of the two masses (Earth) is denoted by m_1 and is separated from the smaller mass (Moon) denoted by m_2, by a distance d. [11]

This problem has no general analytical solutions as does the more familiar two-body problem. However, it does have some very special solutions which are quite useful. There are five stationary points or solutions for this problem. They are depicted in Fig.6 for the Earth-Moon system.



6. Libration Points in the Earth-Moon System [11]

'Stationary' means that an infinitesimal mass would have no motion in the rotating system if placed at the point with zero initial velocity. The stationary points will be referred to as libration points in this paper; although they are also referred to as equilibrium, Lagrangian and Eulerian points. Three of these libration points, known as the collinear points, lie on the Earth-Moon line. In this paper, these are referred to as "translunar" for L_1, "cislunar" for L_2 and "transearth" for L_3. The other two points (L_4 and L_5) form equilateral triangles with the primaries and are called the Lagrangian points. [11]

A stability analysis reveals that the collinear libration points are always unstable. This fact suggests that station keeping would be required to maintain a satellite at the collinear points even in the idealized environment of the restricted three-body world. The equilateral points are found to be stable provided the mass parameter $(m_2/(m_1+m_2))$ is less than 0.0385. This is true for the Earth-Moon system, whose mass parameter is approximately 0.01215058. [11]

The CLP strategy requires twice as many propulsive maneuvers as the LOR strategy (excluding ascent and descent) and therefore a new naming convention was developed. The additional maneuvers occur at the CLP where the LTV is stored, while the crew uses the LEV to explore the Moon. The naming convention is presented in Table 2, with the analogous LOR maneuver acronyms listed for comparison. An overview of the CLP strategy is depicted in Figure 7.

Table 2: CLP NAMING CONVENTIONS

Maneuver	Definition	Corresponding LOR Maneuver
ECLI	Earth-Cislunar Injection	TLI
CLOI-1	CisLunar Orbit Insertion-1	
CLLI	CisLunar-Lunar Injection	LOI
LOI	Lunar Orbit Insertion	
LCLI	Lunar-CisLunar Injection	TEI
CLOI-2	CisLunar Orbit Insertion-2	
CLEI	CisLunar-Earth Injection	
EOI	Earth Orbit Insertion	EOI

The CLP scenario is similar to the LOR strategy

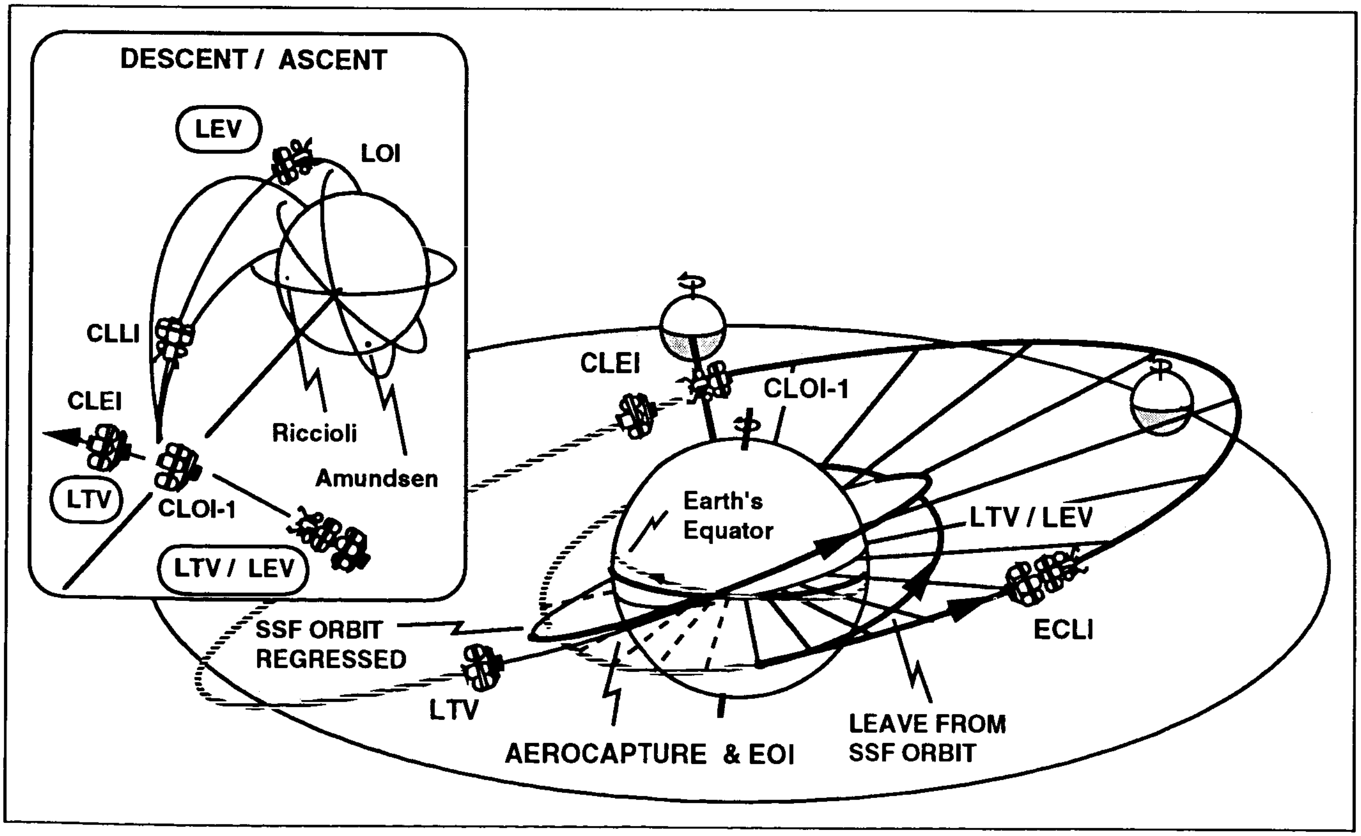


Fig. 7. CLP Mission Architecture

with the exception of the four additional propulsive maneuvers required to stop at and depart from the CLP. On a typical mission, the LTV would depart the space station with the ECLI maneuver and insert at the CLP with the CLOI-1 maneuver. After separating from the LTV, the LEV and crew leave the CLP by performing the CLLI maneuver and insert into an intermediate low lunar orbit with the LOI maneuver. When the proper landing site phasing is attained, the LEV descends to the lunar surface, leaving nothing in lunar orbit. Another option is to land directly on the surface without stopping in an intermediate lunar orbit. However, this generally requires larger changes in velocity (ΔV), due to increased gravity losses. Landing site exclusion zones also exist when using this scenario. [12] These zones can be eliminated with a three burn strategy, but this complicates the mission planning, and can increase the total ΔV requirements. The return scenario uses a similar strategy by ascending to an intermediate low lunar orbit before injecting into a CLP transfer orbit with the LCLI maneuver. The CLOI-2 braking maneuver at the CLP permits the LTV/LEV rendezvous. The crew transfers to the LTV and returns to the space station using an aerocapture technique similar to the LOR strategy. This is accomplished using the CLEI and EOI maneuvers. Notice that, unlike the LOR strategy, the LEV is left at the CLP for reuse on subsequent missions. This is possible because the rendezvous complications associated with leaving the LEV in lunar orbit are eliminated.

Stability analysis has shown that station keeping near the unstable CLP is very little, on the order of one meter per second per year. [13] Thus, storage of the LEV at the CLP would not be a problem from a storable fuel standpoint, but might be a challenging autonomous guidance and navigation problem.

V. Earth Return Options

Another factor which complicates the choice of architecture is how the crew is returned to the Earth's surface. There are three basic Earth return scenarios available for each of the modified mission architectures: (1) capture the crew cab into LEO either propulsively or via an aerobrake maneuver and rendezvous with either the space station, space shuttle, or some other form of crew return vehicle in low Earth orbit which would transport the crew to the surface, leaving the crew habitat in LEO to be refurbished or expended, [5] (2) capture the crew cab into LEO and land either propulsively on dry land, as the cosmonauts do, or glide to a horizontal landing as the shuttle does, [15] or (3) return to Earth on a hyperbolic trajectory, perform a direct entry, splash down 'Apollo-style' in the ocean, and be recovered by ship. [4]

VI. Revised FLO Architectures

After much analysis, two new design requirements were identified by the Exploration Program Office, which necessitated a change of architectures: global lunar access and any-time return capability.

The lunar exploration architecture must make the entire moon available, since the geology is very diverse, and since there is a desire to search for ice hidden in craters at the lunar poles. In addition, the crew must be able to leave the lunar surface to return to earth at any time in case of emergency. [14]

Analysis of the three different staging architectures resulted in the deletion of the requirement of departure from and return to the space station. This was due in part to the following reasons: (1) return to a regressing station node was too constraining on mission planning, (2) free return aborts to station are almost non-existent, (3) architectural dependency upon the station was a high-risk factor, (4) the station node delays treatment in case of medical emergency. [10]

The modified architectures also called for direct entry at Earth with a splash-down and recovery. No other return options were considered viable at that time. [15] The advantages and disadvantages of each option are summarized in Table 3.

VII. Final FLO Proposal

Unfortunately, funding for FLO was cut only months after the contract was awarded. The FLO study was concluded in early 1993 with the recommendation of the lunar direct architecture.

Under this proposal, a new heavy lift launch vehicle capable of placing 225 metric tons in LEO would be developed based on the Saturn V. An unmanned crew habitat, derived from the space station modules, would land autonomously on the lunar surface prior to the launch of the piloted vehicle. The crew transfer module, resembling the Apollo re-entry module would support the crew during the outbound and return legs of the flight and double as a lunar lander, performing the lunar descent and ascent. The crew would transfer to the surface habitat shortly after arrival, and transfer back prior to their departure. The module would perform ballistic re-entry and splash down like Apollo. [16]

This architecture negated the necessity of developing two crew transfer modules and deleted all the phasing problems involved with staging to and from lunar or Earth orbiting nodes. However, this option was the most expensive in terms of initial mass in LEO, and required the development of a heavy lift launch vehicle.

Table 3: Comparison of Revised Lunar Transportation Architectures

Advantages	Disadvantages
Lunar Orbit Rendezvous - Minimizes vehicle mass requirements by leaving parts in LLO - Well suited for near-equatorial sites	- Not well suited for off-equatorial sites due to phasing constraints and very long or short stay times - Any-time return not always available due to earth return phase alignment - Dual crew cab development
Lunar Direct - Provides global access - Any-time abort available - Single cab development - Eliminates orbital rendezvous - Eliminates long-term orbit maintenance	- Sensitive to crew cab mass - Larger launch vehicles required - Cargo transported with crew is more limited - Smaller crew cab implies greater need for prior delivery of a habitat
High Lunar Staging Point - Global access available since plane changes less expensive in high orbit - Any-time abort available - Crew can live out of lander - Provides Moderate payload delivery capability	- Dual crew cab development required - Round-trip travel times can be a few days longer than LOR or Direct

VIII. Beyond FLO

Some figures of merit used in previous studies include: (1) Initial Mass in Low Earth Orbit (IMLEO) requirements, (2) new technology requirements, (3) infrastructure requirements, (4) vehicle development requirements, (5) abort options, (6) mission leg travel times, (7) surface stay times, (8) station keeping requirements / orbital stability (in terms of ΔV), (9) mission planning complexity, and (10) cost in terms of dollars.

In the aftermath of the FLO cancellation, studies on new and revolutionary lunar mission architectures have continued, with emphasis on reducing cost and complexity.

Of all the figures of merit, lowering the IMLEO has perhaps the most direct effect on cutting cost. In addition, reduction in mission complexity, such as rendezvous, docking, and proximity operations, and negation of multiple crew modules, has a major cost benefit, allowing for the development of a simple crew module. The third major cost driver is infrastructure. In general, less infrastructure will mean lower program cost. [17]

Lunar Oxygen Utilization

One revolutionary architecture that could produce the greatest cost reduction relies on the production of oxidizer from lunar soil for use on the return leg of the mission.

Almost half the mass of lunar regolith is trapped oxygen, which can be extracted and refined into liquid oxygen. A number of extraction methods have already been patented, and one has been successfully tested on lunar samples.

Approximately 85% of the propellent mass for oxygen/ hydrogen rockets is due to the oxygen; thus, if the oxidizer required for the return trip (lunar ascent, transearth injection, Earth capture, and deorbit burns) could be manufactured on the moon, the IMLEO could be drastically reduced.

This option would remove the difficulties associated with LOR operations without incurring the mass penalty of the FLO lunar direct architecture, since no Earth-return oxidizer would be taken to the lunar surface. Initial studies show that this architecture could require as little as 1/3 the IMLEO of comparable Apollo-style LOR or FLO lunar direct architectures.

With such drastic mass reductions, the development of a heavy lift launch vehicle would not be necessary. A single shuttle-derived launch vehicle would suffice.

Like the FLO architecture, this so called LUNOX architecture would require the emplacement and checkout of infrastructure prior to launching the piloted mission. Estimates indicate two shuttle-derived launches would be required to deliver the lunar oxygen production equipment.[17]

The cost of the first piloted mission was estimated to be around $19.6 billion, as opposed to the first FLO mission at $25 billion. After a half dozen missions, the savings compared to the FLO option would be $18.5 billion. The development cost of the robotic surface vehicles and oxygen production systems was estimated to be $3.4 billion.[18]

Future Architectures

Another architecture which may hold promise when a strong human presence is finally in place on the moon is the use of a rapid nuclear powered lunar shuttle to ferry crew and cargo back and forth between Earth and lunar orbit.

A proposal by NASA's Lewis Research Center and Aerojet's Propulsion Division envisions the use of a high Isp nuclear thermal rocket (NTR) augmented by a liquid oxygen afterburner to provide a rapid transit shuttle capable of delivering 25 tons of cargo / crew to lunar orbit in 24 hours.

Their scenario envisions workers and cargo being transported to LEO via a scramjet, where they would be transferred to the rapid transit shuttle module. Once in lunar orbit, the module would de-couple and mate with a lander, which would take it to the surface.[18] The surface infrastructure would presumably rely on lunar oxygen to supply the lander taxi with oxidizer for ascent and descent.

IX. Conclusion

The only thing that can be said of lunar mission architectures with any certainty is that they will almost certainly evolve as technology and experience advance.

If ice is discovered in sufficient quantities at the lunar poles, if the mining of helium 3 becomes realistic, or if lunar tourism becomes a reality (as proposed by Japan)[18], cheaper and faster methods of transport will certainly be required.

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LOGISTICS OF A LUNAR BASED SOLAR POWER SATELLITE SCENARIO

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ABSTRACT

A logistics system comprised of two orbital stations for the support of a 500 GW space power satellite scenario in a geostationary orbit was investigated in this study. A subsystem mass model, a mass flow model and a life cycle cost model were developed. The results regarding logistics cost and burden rates show that the transportation cost contributed the most (96%) to the ovarall cost of the scenario. The orbital stations at a geostationary and at a lunar orbit contributed 4% to that cost.

INTRODUCTION

This study was performed in the time period Oct. 1987 to June 1992 as part of a Solar Power Satellite (SPS) Project at the Aerospace Institute of the Technical University of Berlin. The Space Power Satellite system is a large number of photovoltaic space power plants partially manufactured and assembled in geostationary orbit. They deliver electrical energy via microwave to rectennas on earth for distribution to consumers. The major driver for this type of analysis was the assumption, that the energy production and supply on earth using solar power satellites at a geostationary orbit can only be provided at economically competitive prices, if the solar satellites and the geo-infrastructure are fabricated and implemented using lunar resources in addition to the resources provided from the earth surface: the use of lunar resources reduces the logistics cost up to 67% compared to an "all earth" resources scenario. Several studies were already performed analyzing, e.g., the impact of alternative propulsion types utilized for the scenario, or optimizing the design and fleet composition of such a scenario involving earth and lunar resources. This study aimed to identifiy the basic parameters with respect to the type and cost of the logistics support associated.

THE SCENARIO

In order to perform the analysis a survey of related publications was made, relevant studies were reviewed and a logistics scenario was established. The scenario considered the development, on-orbit integration and operations of a 500 GW solar power satellite system consisting of 111 5-GW-Satellites in a geostationary (GEO) orbit, its supporting GEO- and LUNAR-Infrastructure, as well as the dedicated logistics orbital stations and resupply launchers and vehicles.

The scenario started with the early deployment and operations of an exploration base on the lunar surface early in the 21st century. This first lunar outpost was to be developed into an exploitation Lunar Base with up to 16 facility elements. The Lunar Base was to provide mining, production, manufacturing and power generation facilities, as well as habitation facilities and a Lunar Spaceport, where up to 800 people (peak) were to live and work. The Lunar base was to export to the geostationary infrastructure among others raw and construction materials for satellite subsystems and structures, microwave converters and liquid lunar oxygen as propellant.

Parallel to the Lunar Base development, there was also to be a strong build up phase of the geostationary orbital infrastructure (GEO-Complex). It was to start with a demonstration flight unit of a 10 MW Solar-Power-Satellite in low earth orbit (LEO) and a 500 MW prototype in geostationary orbit. The further assembly and integration of a total of 111 5-GW-Satellites was to be performed in GEO at dedicated orbital assembly and maintenance facilities, supported by habitation, laboratory and space port facilities. The production peak with up to 600 people would arise at about year 40 after operations start. The GEO-Complex was to consist of up to 10 orbital facilities. The transportation and distribution of pressurized and unpressurized cargo, propellants, pressurants and other supplies and the rotation of crew members was to be performed by a local transportation company (Geostationary Regional Transportation Company, GRET), which served 39 routes in GEO with a fleet of vehicles of different types. After the peak there were only maintenance and post-production activities assumed.

The earth facilities were to provide the liquid hydrogen, propulsion subsystems, as well as electronics, crew supplies and other dedicated equipment to the lunar and to the geostationary infrastructures. The study logic is shown on figure 1.

THE DEFINITION OF THE LOGISTICS SYSTEM

The Logistics System supported through its elements the build up, the operations and the phase out of a Solar Power Satellite System by providing the transportation, storage and distribution functions for the GEO-Complex and for the Lunar Base, figure 2. The transportation function was performed through dedicated launchers (Heavy Space Freighter, HSF) and vehicles (Orbital Transfer Vehicle, OTV). The storage and distribution function was performed by dedicated orbital stations in GEO (Geostationary Space Operations Centre, GEO-SOC) and in lunar orbit (LUO-SOC).

GENERAL ASSUMPTIONS

The analysis of the implementation and evaluation of a cis-lunar logistics system was carried out under the following assumptions and ground rules:

- o Transportation of the Lunar Base elements and supplies by reusable Heavy Space Freighters (HSF) based on the NEPTUNE concept design introduced in /2/.
- o Transportation of lunar crew and crew related supplies by large capsules (third stage of HSF).
- o Establishment of a Lunar Space Operations Centre in low lunar orbit as a transportation node for maintenance and fueling of space vehicles.
- o Use of reusable, chemical propelled orbital transfer vehicles with aerobrake return from lunar and GEO orbit to earth orbit. The third stage of the HSF (cargo OTV) return to the earth surface.
- o Utilization of lunar produced LOX for the propulsion of the orbital transfer vehicles departing from GEO-Complex, lunar orbit and surface. All liquid hydrogen is produced on earth and distributed to GEO and Lunar Base by the HSFs and OTVs.
- o Establishment of a Geostationary Space Operations Centre in the GEO-Complex as a transportation node for maintenance and fueling of space vehicles.
- o Transportation of GEO-Complex elements and supplies by reusable HSFs.
- o Transportation of GEO-crew and crew supplies by large capsules.
- o Stay time of the crew at GEO facilities and on the Lunar Base is 6 months on an average.
- o An overall time period of 50 years was considered for scheduling and life cycle cost estimation.

THE MODELS

Three models were developed for the analysis of the logistics parameters:

- o the mass analysis model
- o the mass flow model
- o the life cycle cost (LCC) model

MASS ANALYSIS MODEL

It served as a tool for the evaluation and analysis of the subsystem mass of the Space Operations Centres and Orbital Transfer Vehicles. The objective of the model was to develop algorithms for the estimation of mission and design dependent subsystem mass data. These mass data were used for cost evaluation purposes in the LCC-Model.

Space Operations Centre

The mass breakdown was performed considering mission dependent (product tree approach) and technical layout (work break down structure approach) functions of a Space Operations Centre. The technical design of a SOC was derived from the second stage of the NEPTUNE heavy launcher concept.

SOC Net Mass	(Mg)
Structure	91.91
Propulsion	0.12
Propellant Tanks	26.11
Attitude Control	7.37
Pressur. Habitation	87.06
Pressurized Storage	25.68
Truss Structure	14.48
MicrometeoridProtection	38.44
Servicing Facility	57.66
Docking/Berthing	8.89
Refuelling/Reliquefaction	8.74
Robotics	10.30
OrbitalSupportEquipment	7.31
Spares	1.22
Scientific Facilities	1.74
Power Generation	20.48
Crew Safeguard/Escape	15.16
Total Net Mass On-Orbit	422.67
Tank Capacity	1404.75

Table 1: Reference subsystem mass of a SOC

The reference layout concept of a SOC is depicted on figure 3. The SOC consists of structure, habitation modules, storage modules for pressurized cargo, facilities for unpressurized cargo storage and for docking and berthing, handling and servicing of

OTVs. Mass algorithms were developed for each of the SOC subsystems established, see table 1 for mass breakdown. The SOC initial launch mass calculated is approx. 1800 Mg, the net mass 422 Mg.

Orbital Transfer Vehicle

The mass breakdown of the OTVs was derived from already established design concepts based on chemical propulsion subsystems, i.e. liquid oxygen/liquid hydrogen. It was further assumed that a few types of vehicles would perform all the logistics flights. A fleet of modular cargo/propellant vehicles (cargo OTV) and crew vehicles (passenger OTV) had to transfer cargo, propellants and personnel to GEO and to the Lunar Base autonomously. The dimensioning of the vehicles was performed for the leg LUO->GEO, because of the traffic density experienced there. The cargo OTV has a calculated launch mass of 204 Mg (payload 100 Mg) and the crew OTV 83 Mg (payload 23 Mg).

MASS FLOW MODEL

The mass flow model was developed for the simulation of the primary mass flows between the infrastructures on the moon, the GEO-Complex and the terrestrial surface.

The overall mass flow is depicted on figure 4. The major system variables, which were used as input parameters for each scenario year to the mass flow model, were:

- o Length of the design and development phase (years)
- o Length of the operations phase (years)
- o Length of the phase-out operations (years)
- o Number of working persons in GEO
- o Cargo mass from Lunar Base to GEO (Mg)
- o Lunar oxygen mass from Lunar Base to GEO (Mg)
- o Terrestrial hydrogen mass from Earth to GEO (Mg)
- o Number of working persons on the Lunar Base
- o Cargo mass from Earth to Lunar Base (Mg)

Through the processing of the input values the following logistics parameters were calculated for each year of the cis-lunar scenario:

- o Number of HSF launches and OTV flights for each traffic route of the scenario
- o Storage requirements for cargo and cryogenic propellant mass on the SOCs
- o Working hour requirements for SOC operations in GEO and LUO
- o Logistics cargo and propellant mass requirements for SOC operations in GEO and LUO
- o Logistics crew resupply mass and OTV resupply mass requirements
- o SOC and OTV maintenance working hour requirements

The integration of the SOC activities in the scenario is depicted on figure 5. The main variables of the primary mass flow of the scenario, i.e. cargo, propellants and passengers, are shown. Parallel to the primary there is the secondary mass flow for the logistics resupply of the SOC in terms of own (SOC) resupplies, e.g. maintenance, propellant and crew, as well as the resupplies for the OTVs, i.e. maintenance and propellant. The services provided by each SOC are also shown as an output of the station. The services provided are measured in working hours and are divided into services for the GEO and the Lunar Base cargo, for the OTV ferries and services for the own SOC-subsystems.

Through the simulation of the primary cargo and propellant mass flow required for the Solar Power Satellite operations, the mass flow of the logistics support required, or secondary mass flow, was derived. The ratios of primary to secondary logistics support parameters were established as logistics burden rates for mass and workload for the overall logistics system in geostationary and lunar orbit. The analysis revealed that the SOC in the lunar orbit require the largest amount of propellants for the OTV ferries to the GEO. This is explained due to the fact that the ferries from lunar orbit to GEO must carry all the propellant for the trip to and back from GEO. This amount of propellant in LUO influences the overall logistics mass burden rate of 751 (kg/Mg) established, i.e. to every 1000 kg cargo mass transported through the logistics system 751 kg of logistics support mass are required by the logistics system itself. 99.8% out of that support mass consist of propellant for the OTV transportation activities. The corresponding burden rate for workload is 0.25, i.e. 25% of the actual services (working hours) provided by the two SOCs are required for the own subsystem and OTV support activities.

LIFE CYCLE COST MODEL

The objective of the life cycle cost model was to establish cost figures for the logistics support provided by the SOCs and the orbital ferries. Through the LCC model the overall cost of the cis-lunar logistics system utilized was estimated. The LCC model is depicted on figure 6. Cost algorithms were developed for the calculation of the SOC development and production cost using Cost

Estimating Relationships (CER) of the following type:

$$C = a\,M^{x}$$

where

C =	cost in manyears
a =	system specific parameter
M =	Subsystem mass in kg
x =	cost specific parameter

In order to apply the CER algorithms to the elements of the SOC, the SOC mass was broken down to a lower level, e.g. the mass of the pressurized modules was described through structure, electrical, electronical and mechanical subsystem mass.

Further assumptions of the LCC model:

- o Commonality factors were established considering the parallel development of the SOC subsystems, a fact which leads to a lower overall development cost.
- o The cost figures were calculated in manyears and then transformed into \$(1990); the value manyear is not influenced by inflation.
- o No detailed cost analysis was performed for the OTV development and production, since this analysis was already done in other studies. Instead transportation cost figures were derived, and transportation prices were established for each leg of the traffic model and vehicle type.
- o The design, development and production of the SOC lasts 10 years, the implementation and build up 4 years. With the operations start of the LUO-SOC begins the operational phase of the LCC model (50 years).

The following major cost groups were established, see figure 6:

- o Amortization Cost
  The amortization cost considers the amount of SOC development cost, the non-recurring production cost and the acquisition cost for ground support facilities. The amortization cost is distributed over the operational phase of the scenario. No interest rates were charged on the investments because the program was assumed to be financed with public funds.
- o Indirect Operations Cost
  This cost category considered all the cost of the personnel, facilities and services on earth, e.g. SOC mission control.
- o Direct Operations Cost
  The direct operations cost includes all cost elements of the on-orbit SOC operations and OTV transportation flights, e.g. SOC-personnel, transportation cost, external services of Lunar Base.
- o Recurring Cost
  The recurring cost includes the cost elements for the system engineering, the follow on production of SOC-subassemblies for preventive maintenance, the spares and repair parts as well as their integration and test.

The total SOC-development cost for the 1st flight unit is calculated to approx. 17,8 billion \$(1990) and the production cost to 7,8 billion \$(1990). The overall life cycle cost of the cis-lunar market and the life cycle cost of the SOC logistics system were also calculated. The overall cis-lunar market includes cost figures for the overall payload (cargo) transported to the GEO-Complex and the Lunar Base in the frame of the SPS scenario, while the life cycle cost of the SOC logistics system includes the cost elements of the two orbital stations (operations) themselves and the supporting flights only.

OVERALL MARKET

Since the calculated quantitative cost figures are valid for the particular scenario and the assumptions applied, it was more interesting to find out qualitative figures, i.e. cost allocations in (%) of the stations and vehicles in the cis-lunar market. Provided that the average annual cost of operations in the overall cis-lunar market was calculated to approx. 80 billion \$(1990), the transportation cost represents the largest amount with 96%. The distribution of the calculated cost percentages over the life cycle of the market and the stations is depicted on figure 7. The specific cost for cargo mass transported and distributed through the stations in LUO and GEO was estimated to approx. 760 \$(1990) per kg mass. 75% of that cost fall into GEO-SOC due to the high mass flow rates and the associated cost, and 25% into the LUO-SOC.

LOGISTICS SYSTEM

The specific logistics cost at the two space stations was calculated to 27 \$(1990)/kg, i.e. 27 \$ for each kg cargo mass transported through the logistics system of the LUO and GEO stations, and represents 3,6% of the overall life cycle cost. The major contributor to the LCC of the orbiting stations is the recurring cost (35,4%) of the stations hardware. The transportation cost contributes 9,6% to the overall station cost, see figure 8.

The cost for personnel on the SOCs was calculated for both LUO and GEO, pending on the workload, the traffic density of the stations and the cargo mass flow. The personnel cost consisted of cost elements for crew transportation, crew training, on-orbit life support and salary. Specific cost figures were also derived for on-orbit working hours. As an average value 5000 \$(1990)/hour was calculated for the GEO-SOC. The specific cost of a working hour at the LUO-SOC was in the range of 30% of that value. The on-orbit stay time for the crew members was rated accordingly to approx. 12,5 million \$(1990) per person per year. The cost of the LUO-SOC was approx. 32% lower than that of the GEO.

Specific cost elements for the incoming and departing ferries, as space port fees, were also derived by applying the cost figure 27 \$/kg payload mass and station specific factors. This amount was distributed to 93% to the LUO station and 7% to the GEO station. This was due to the fact that the ferries were transferring full loaded cargo mass from LUO to GEO and returning back empty (mass flow direction). Passenger ferries were carrying in both directions crew members and showed rather balanced figures; the fees for passenger ferries were distributed to 54% to the GEO station and to 46% to the LUO station.

An impression of potential clusters of space operation centres in GEO and LUO is given on figure 9. The analysis indicated a higher demand on propellant storage capabilities in the lunar and a higher demand for space ferry operations in the geostationary orbit.

SUMMARY

The logistics analysis of the operations of a lunar based solar power satellite scenario revealed that the transportation cost is the major contributor (96%) to the overall cost of the cis-lunar market. Logistics burden rate evaluations indicate that 0.75 kg of logistics mass for each kg of cargo mass and 0.25 maintenance hours for each working hour for cargo servicing were required. The average life cycle cost of a logistics system comprised of two orbital stations in geostationary and lunar orbit including the dedicated resupply flights was approx. 2.7 billion \$(1990) per year.

The logistics system of the two stations analyzed in this paper is only a part of the overall system in GEO and LUO. Since the real demand on logistics support and services depend on the cis-lunar market, the optimization of the whole system, i.e. orbital stations plus launchers plus orbital ferries, may lead to a reallocation of functions and services envisaged and thus influence the cost figures presented. Logistics cost elements and burden rates contribute the most to a transparent evaluation and economic trade off analyses of alternative scenarios and their supporting infrastructures.

LIST OF ACRONYMS AND ABBREVIATIONS

GEO	Geostationary Orbit
GRET	Geostationary Regional Transportation Company
HSF	Heavy Space Freighter
LCC	Life Cycle Cost
LOX	Liquid Oxygen
LUO	Lunar Orbit
OTV	Orbital Transfer Vehicle
SOC	Space Operations Centre

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BIOGRAPHY

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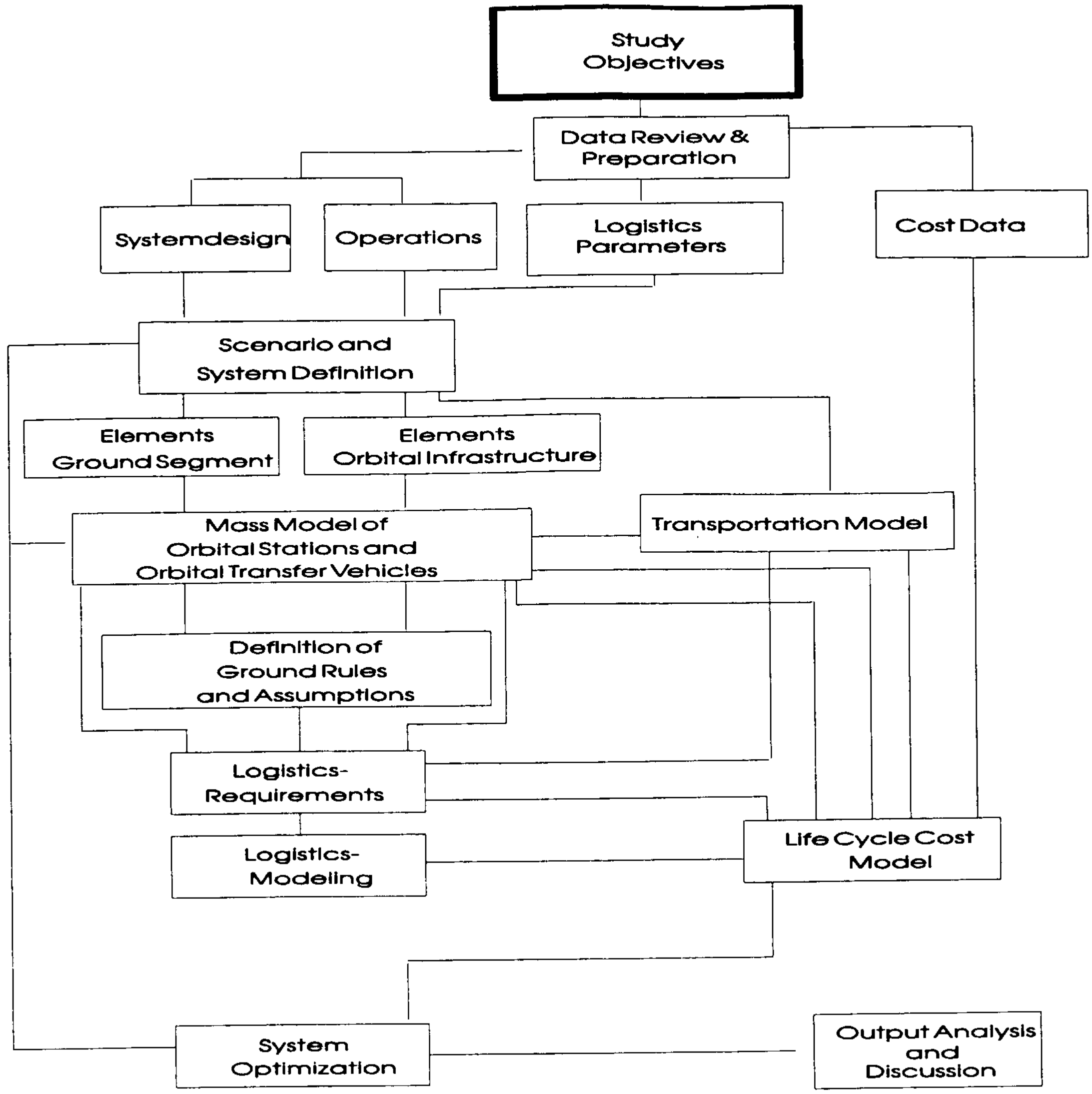

Figure 1: Study logic

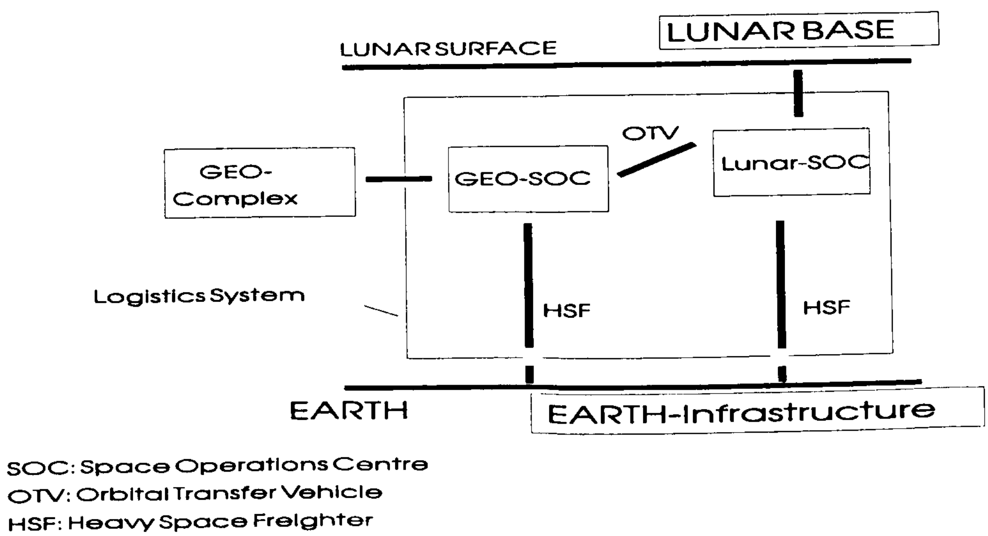

Figure 2: Cis-lunar scenario

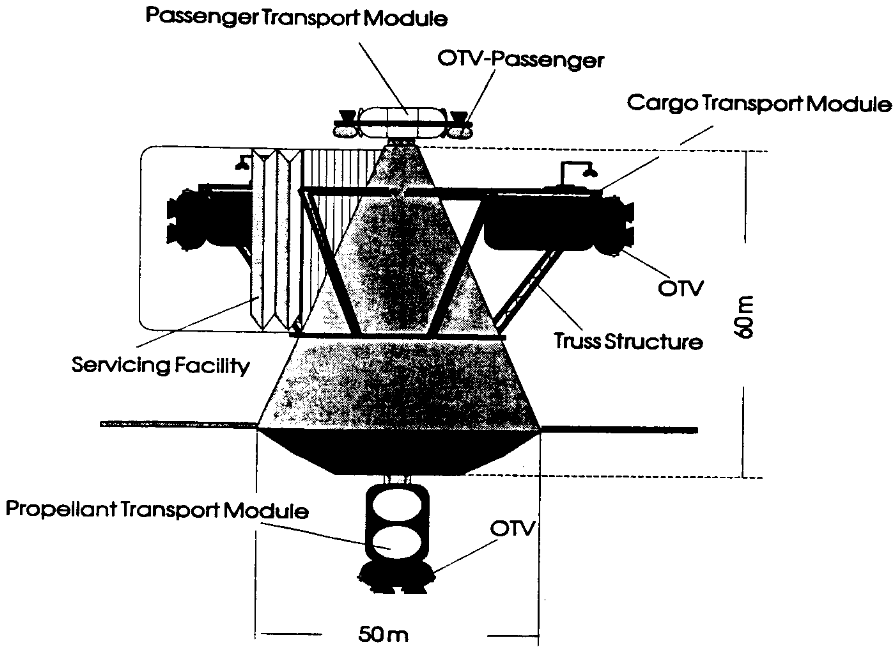

Figure 3: Reference SOC configuration

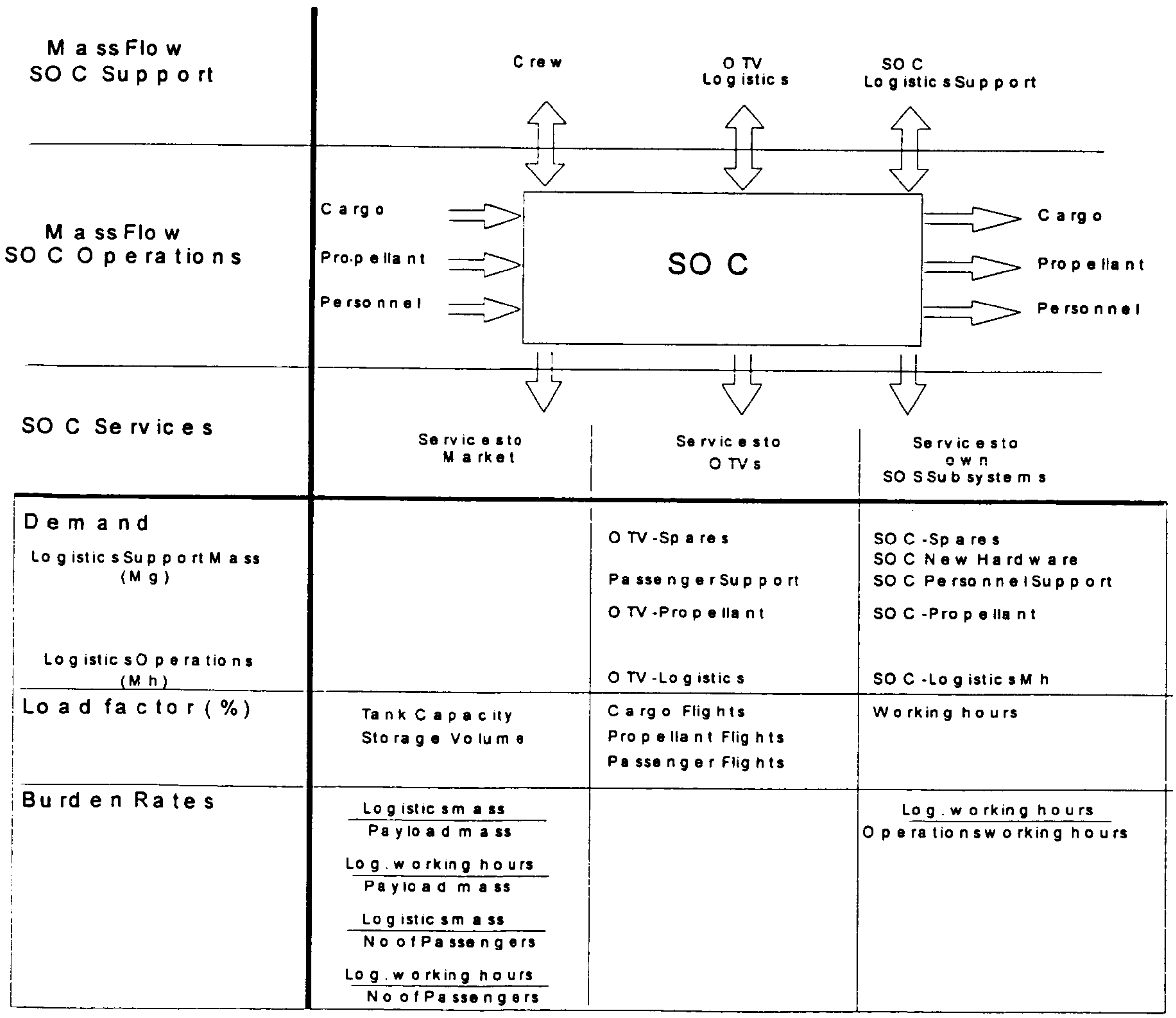

Figure 4: SOC mass flow categories and output

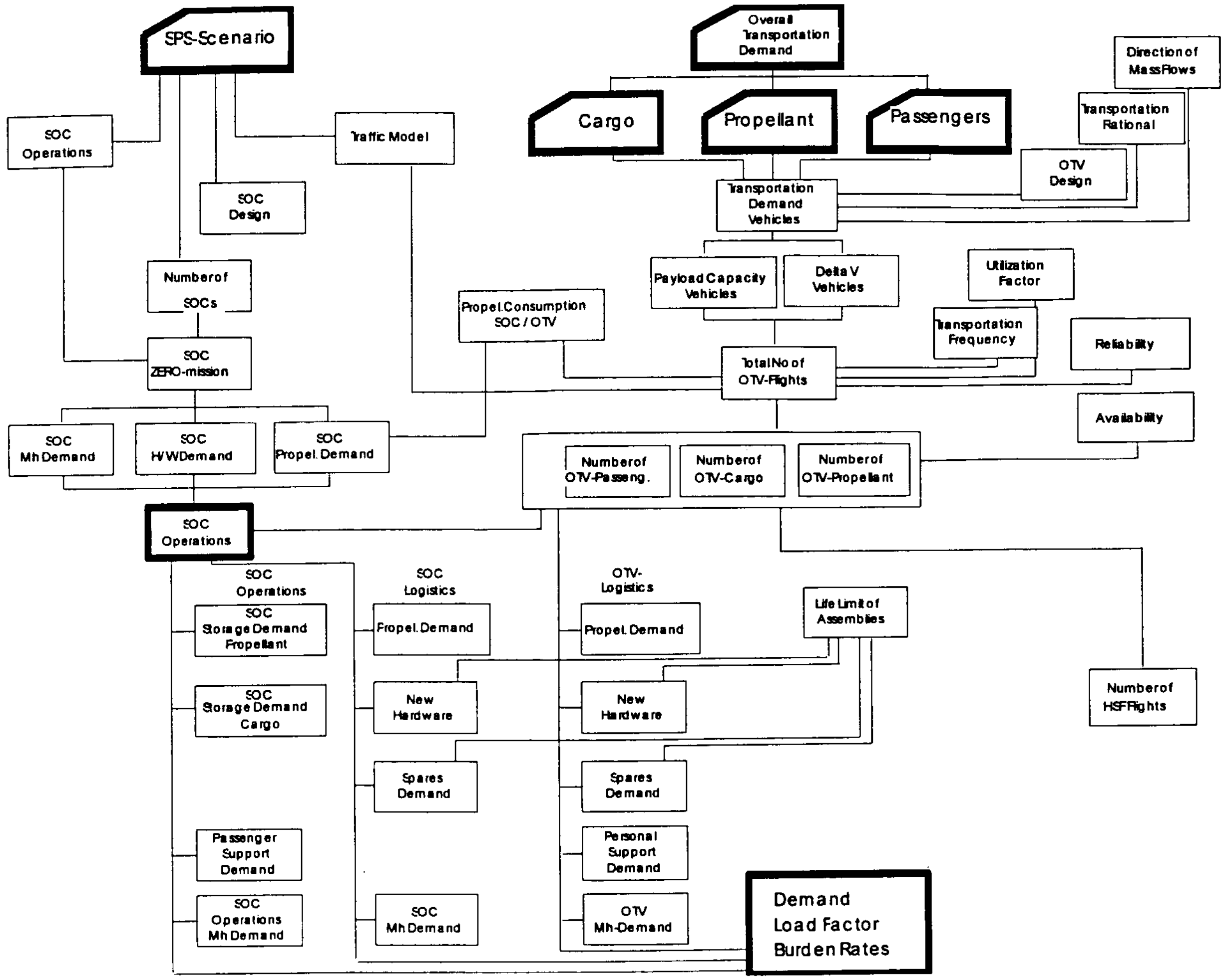

Figure 5: Mass flow model

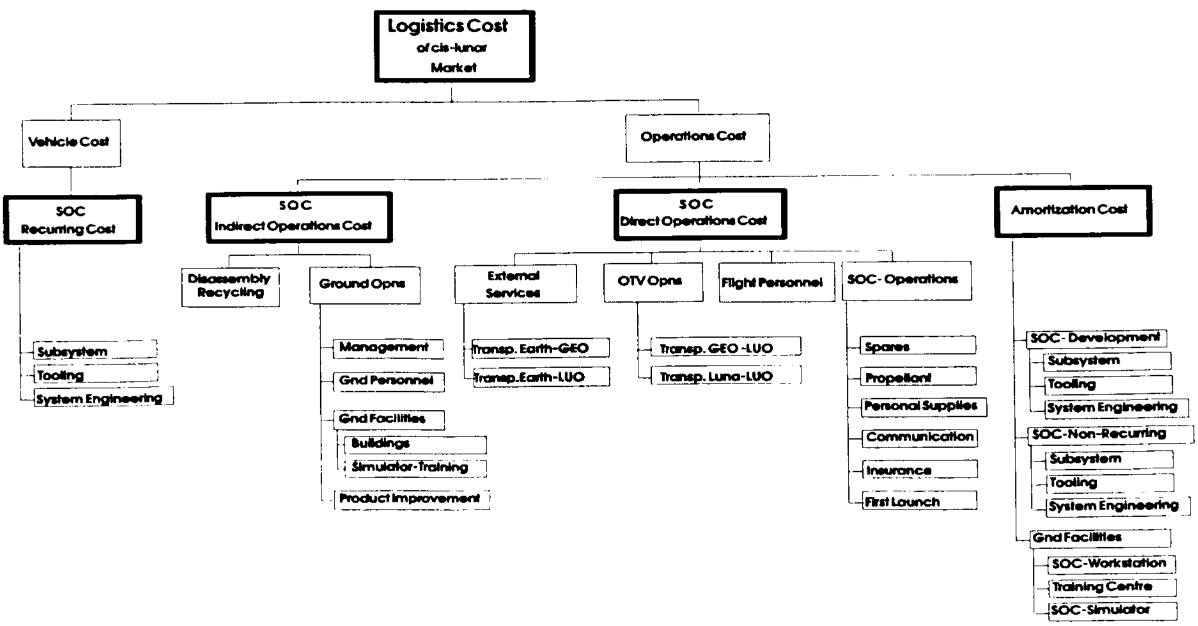

Figure 6: Life cycle cost model

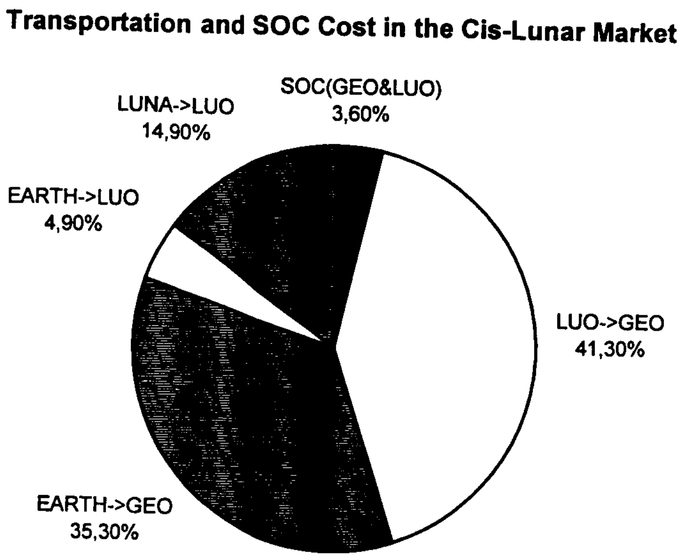

Figure 7: Allocation of cost in the overall cis-lunar market

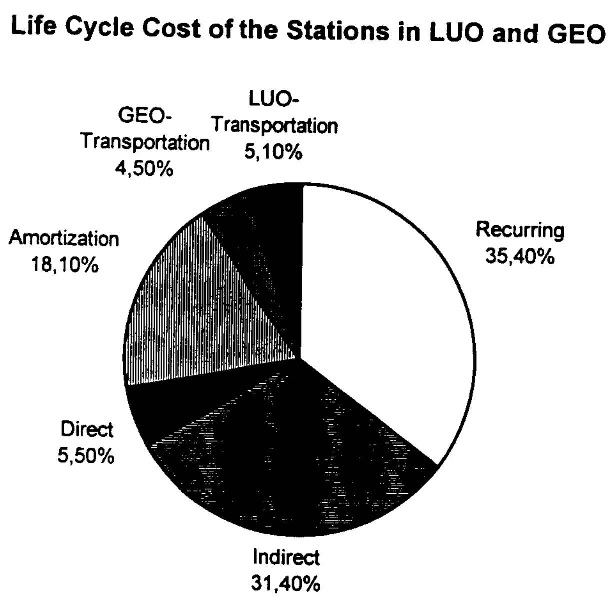

Figure 8: Allocation of stations cost

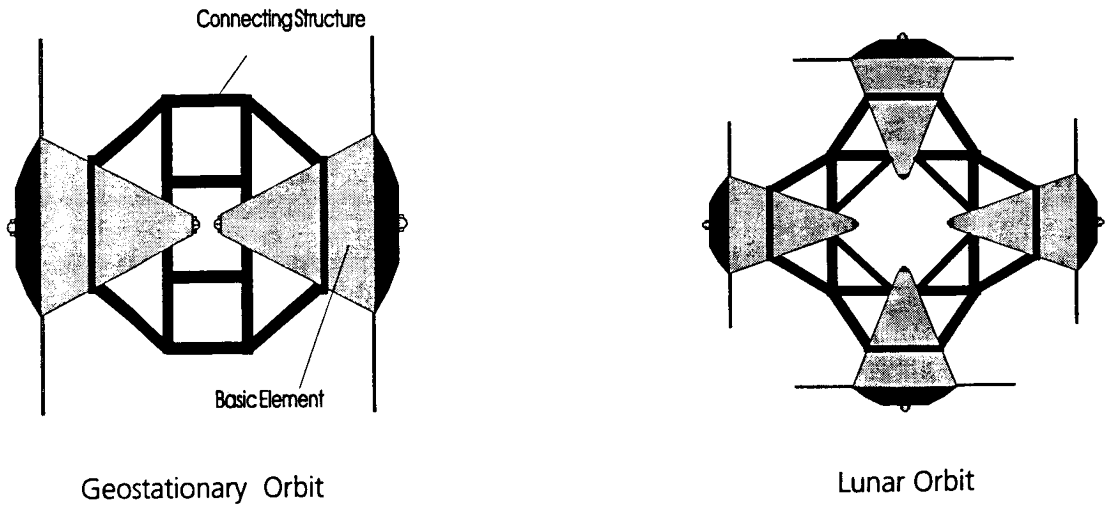

Figure 9: Example of SOC-clusters in GEO and LUO

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THE U.S. COMMERCIAL SPACE LAUNCH PROGRAM AND THE DEPARTMENT OF DEFENSE DILEMMA

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Introduction

The U.S. space launch program no longer dominates the world and is now playing "catch-up" with the world's first commercial launch company, Arianespace. A healthy U.S. commercial launch program is essential and will assure continued low-cost military access to space. The effort to regain the lead in commercial space launch market has been hindered by declining Department of Defense budgets. President Clinton's space policy prohibits expensive new launch vehicles and limits the Department of Defense to low cost upgrades of existing launch vehicles. The U.S. government created the space sector and must ensure a smooth and effective split from the emerging commercial space program in order to regain world dominance. Until U.S. government and commercial ties are severed, the Department of Defense must consider commercial space launch interests when making military decisions.

Ariane provides an excellent "bench mark" for the U.S. to base future launch vehicle upgrades. Ariane advantages were identified and low-cost recommendations have been made. If the U.S. sets the target of first equaling and then surpassing Ariane by incorporating these recommendations, then the U.S. could once again dominate the world commercial launch market and ensure low cost military access to space.

Does the U.S. have a commercial space launch problem?

The U.S. space industry lost its lead in launching commercial satellites several years ago, and is falling further behind every day. The United States, for seventeen years from 1965 to 1981, launched every commercial satellite. The world's first and only commercial space launch company, Arianespace, is responsible for taking the lead away from the United States. Arianespace now dominates the commercial launch market by launching 65% of the world's commercial satellites.[1] The entry of China, Japan, and Russia further reduced U.S. launches to less than 26% (Figure 1). An estimated $1 billion each year is lost to outside space launch competition. The demise of the U.S. commercial launch business will continue at an ever increasing rate with the emergence of the Chinese, Japanese, and Russian commercial space launch programs and the debut of the Ariane 5. The future for U.S. commercial space launch business looks grim unless immediate corrective action is taken.

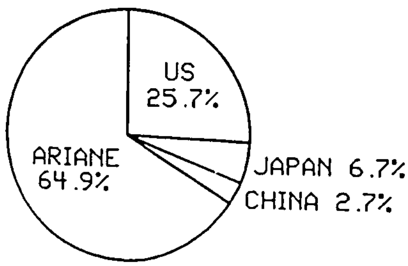

FIGURE 1. COMMERCIAL SATELLITE LAUNCH VEHICLES, 1988-1992, 74 SATELLITES

Why should anyone care about the U.S. commercial launch program?

Why should the American public care whether or not the U.S. commercial space launch business is lost to foreign competition? There are four reasons why Americans should be concerned about the U.S. commercial space launch future.

The first and probably the most important reason is the economic future of the United States. The standard of living for Americans depends on the economic health generated by successful worldwide competition. The rules of worldwide trade will be written by those who dominate the market and everyone else will have no choice but to play by those rules.[2]

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The second reason is the concern for excessive expenditures of tax dollars. Military space programs consume a large amount of tax dollars and every effort should be taken to keep those costs down. Competitive commercial space launch businesses can help keep military expenditures down for those companies that take on both commercial and military contracts.

The third reason is national security by providing continued access to space for the U.S. military. A healthy U.S. commercial launch program will assure continued low cost military access to space because of shared technology between the government and commercial sectors.

The fourth reason is national pride, which has driven many previous space activities. President Kennedy was the best example of one man who pulled the nation together for the race to the moon because he believed that the United States could not be second in the eyes of the world, because second was last.[3] The American people should be concerned about the future of the U.S. commercial space launch program.

What has the government done to help the commercial space launch program?

Each of the mainstay launch vehicle manufacturers (Atlas, Delta, and Titan) have been products of a nineteen sixties government sponsored space race. The government needs to support the emergence of a commercial launch program from the womb of the original government dominated space program. The separation of government and commercial programs has been a slow and difficult process that is far from complete. Government, military, and commercial launch programs have been interwoven into a maze of restrictive, overlapping, inconsistent, and politically driven U.S. space policies.

The U.S. government has conducted numerous surveys and organized many committees to research the space program problem and provide recommendations to Congress. During the last administration, The Vice President's Space Advisory Board Report, November 1992, and the Final Report to the President on the U.S. Space Program, January 1993, both recommended a new family of launch vehicles and centralized management. The U.S. fiscal crisis worsened with the end of the Cold War and military budgets became easy prey for the fiscal feeding frenzy of the last thirty years.[4] A number of President Clinton's initiatives are under way to again study the problem and recommend a less expensive plan of action.[5] A recently released draft of the Clinton's launch policy recommends that the military be limited to improving existing launch vehicles for military payloads.[6] The U.S. military has been limited to low cost incremental changes to the existing older Atlas, Delta, and Titan launch vehicles for improving both the military and commercial space launch programs.

Why does the government need to rescue U.S. commercial launch companies?

U.S. commercial space launch programs need to be freed from burdensome policies that prohibit rapid and consistent decisions that are required of competitive programs. The following example shows how a simple government decision to modify a launch pad destroyed commercial opportunities for Martin Marietta. An earlier government decision to convert a Titan 3 to a Titan 4 launch pad left only one Titan 3 launch pad capable of launching commercial satellites. True, there was a second launch pad on the west coast, but it has never been capable of launching commercial satellites into their required geostationary orbits. Martin Marietta's, commercial division, launched just three satellites before the only remaining launch pad was shut down for Titan 4 modifications. The launch pad was out of commission for two years and all commercial Titan 3 launches were terminated while customers sought launches elsewhere. For the benefit of the nation and the future of the U.S. commercial space launch programs, the government has an obligation to ensure a smooth and effective split between government and commercial space launch programs.

Why has Ariane been able to capture the commercial launch market?

Arianespace recognized the potential of commercial space transport and built a line of launch vehicles tailored specifically to the needs of the world's commercial satellite organizations.[7] The Ariane family of space launch vehicles is specifically designed to deliver payloads directly to geostationary transfer orbit because commercial payloads are geostationary communications and observation satellites. They offer sixteen different launch configurations that cover a broad range of payload sizes at consistently low prices. Ariane also offers multiple launch capability that allows all sizes of satellites to be matched to one of the sixteen different launch configurations to achieve a consistently high maximum payload. The Kourou, French Guiana launch facility is located near the equator, which provides a 15% energy savings over U.S. launched spacecraft bound for geostationary orbit.[8] The large family of Ariane space launch vehicles offers a number of significant advantages that help explain why Arianespace has captured the commercial launch market.

<u>What about other foreign launch competition?</u>

China, Japan, and Russia have launch vehicles capable of providing tough competition with the United States. Launch competition from these three countries has been temporarily held at bay because of satellite export restrictions from the United States. U.S. companies still build most of the world's commercial satellites even though foreign competition is thriving. Sixty nine percent of all the world's commercial communications satellites scheduled for delivery from 1992 to 1997 will be built by a U.S. prime contractor.[9] The U.S. government has placed a number of export bans on U.S. built commercial satellites to foreign countries in order to protect the U.S. commercial launch business.

The major reason for export bans has been the unfair pricing advantage of government subsidized launches. Export licenses of U.S. manufactured satellites have been withdrawn from China for accusations of price dumping, internal human rights disturbances, and missile proliferation.[10] Concerns over unfair Chinese pricing prompted the U.S. government in 1988 to limit satellite exports to nine by the year 1994, and all costs would be compatible with the international launch market.[11] The Russians have also been denied export licenses, in 1989, for U.S. manufactured satellites for reasons of illegal technology transfer and price dumping. President Bush reversed the decision in 1992, and approved one launch of a U.S. built satellite.[12] A more recent U.S and Russian agreement was reached in 1993 that allowed eight Russian Proton geostationary commercial satellite launches through the year 2000.[13] Both the Chinese and Russians have obtained commercial satellite contracts that have been outside the jurisdiction of the United States, which explains their gradual growth of the commercial satellite market.

The Japanese, on the other hand, have not offered competitive prices to foreign commercial satellite customers. The earlier N1 and H1 launch vehicles were hybrid American and Japanese designs that were never price competitive even though they were very reliable. The new all Japanese H2 is one of the world's most efficient heavy launch vehicles, but the high development costs have temporarily prohibited competitive launch pricing.[14] The Japanese intend to reduce the costs of their H2 to make them competitive with the Ariane, by simplifying production with increased automation and reducing material costs by using cheaper materials and simpler structures.[15] Another tremendous setback for the Japanese H2 is the internal environmental restriction of only four launches per year to protect the nearby fishing industries from unnecessary loss of fish.[16] The Japanese H2 will become a competitive launcher of commercial satellites only when and if they can bring their prices down.

<u>How will the U.S. compete with the emerging foreign launch competition?</u>

Americans do not seem to care that they are falling behind the most advanced part of the industrial world. Their most comfortable hypothesis is the belief they do not need an economic game plan.[17] For nearly a decade, Ariane has been consistently launching more commercial satellites than the all of the U.S. launch vehicles combined. Many years have passed without a concrete plan to maintain the lead or at the least, keep up with foreign competition, especially Arianespace. Now, the U.S. has found that playing "catch-up" is considerably more difficult than keeping up with foreign launch competition. Lester Thurow, author of <u>Head to Head</u>, provides the steps required to catch up with the competition.

> A country that wants to win starts by closely studying the competition. The purpose is not emulation but what the business world calls "bench marking." Find those in the world that are best at each aspect of economic performance. Measure your performance against theirs. Understand why they are better. Set yourself the target of first equaling, and then surpassing, their performance.[18]

Arianespace was selected as the "bench mark" for this study because of their significant performance and outstanding success in capturing a majority of the world's commercial geostationary launch market. Their performance was then compared to U.S. launch vehicles in four areas that were identified as being important: (1) payload characteristics, (2) costs for delivery, (3) launch vehicle selection process, and (4) technology. Space launch program comparisons uncovered a number of differences that gave Ariane a significant advantage and those differences evolved into "catch-up" and "get ahead" recommendations.

The first measure of performance: payload characteristics

Payload characteristics were selected as the first performance standard because of their importance to the launch vehicle. The sole purpose of the launch vehicle is to deliver a payload to a particular stellar location. The world's space launch vehicles have placed 392 communications and observation satellites into 22,300 mile geostationary orbit from 1965 through 1992. A little more than 50%, 198, of those have been commercial satellites that have cost about $12 billion, 1993 U.S. dollars, for delivery to orbit. Because the U.S. had such a strong lead in the beginning, Ariane still has only launched 66 compared to 117 U.S. launched commercial satellites (Figure 2).

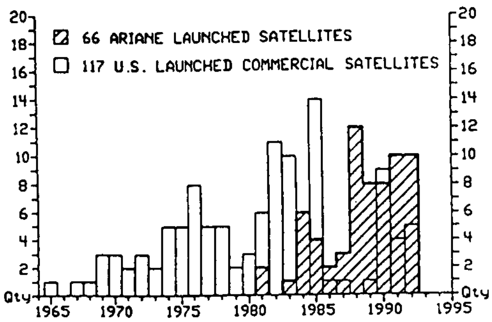

FIGURE 2. ARIANE VS. US LAUNCHED COMMERCIAL SATELLITES

Arianespace's goal, from the very beginning, has been to launch half of the world's commercial satellites.[19] Their goal will become a reality within the next few years.

An average of fifteen commercial satellites per year are now being launched and that number will steadily increase if past trends continue.[20] Average payload weights have also steadily increased (Figure 3) from the first 39 kg (86 lb) Intelsat 1 to an average of nearly 1200 kg (2700 lb).[21] Payload quantities and size will continue to increase in the foreseeable future. Ariane closely monitors increasing payload sizes and ensures that their vehicle upgrades keep up with commercial needs. U.S. launch vehicles, on the other hand, are still being tailor made to specific military payloads.

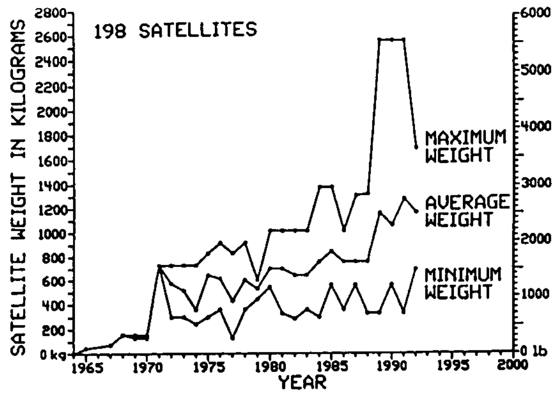

FIGURE 3. COMMERCIAL SATELLITE WEIGHT, 1965-1992

The second measure of performance: launch costs

Commercial satellites typically are designed to go to higher, more expensive, geostationary orbits where they travel in synchronization with the Earth's rotation and appear to be stationary. Space launch vehicles take only the payload and a booster motor to an orbit called a geostationary transfer orbit (GTO). A GTO is a highly elliptical orbit used to take the payload out to 22,300 miles where the satellite booster motor fires to move the satellite into its final circular geostationary orbit (GEO). Launch costs were estimated using payload costs per pound to reach a geostationary transfer orbit. The overall cost for a flight was divided by the payload weight to obtain the cost per pound rate. The U.S. Atlas, Delta, and Titan launch costs were compared to the "bench marked" Ariane for all commercial flights from 1988 to 1992.

The Atlas 1/2, Delta 2, and the Titan 3 cost per pound rates were all unbelievably less than Ariane 4 by as much as 25% (Figure 4). How can this be true after hearing all the accusations of U.S. launch vehicles being too costly? The lowest rates were commonly achieved by U.S. launch vehicles carrying military satellites. Military satellites typically used 100% of the payload capacity for the tailor-made U.S. launch vehicles.[22] Commercial satellites have been poor matches to U.S. launch vehicles and averaged less than 80% of the rated payload capacity.[23] Ariane payloads,

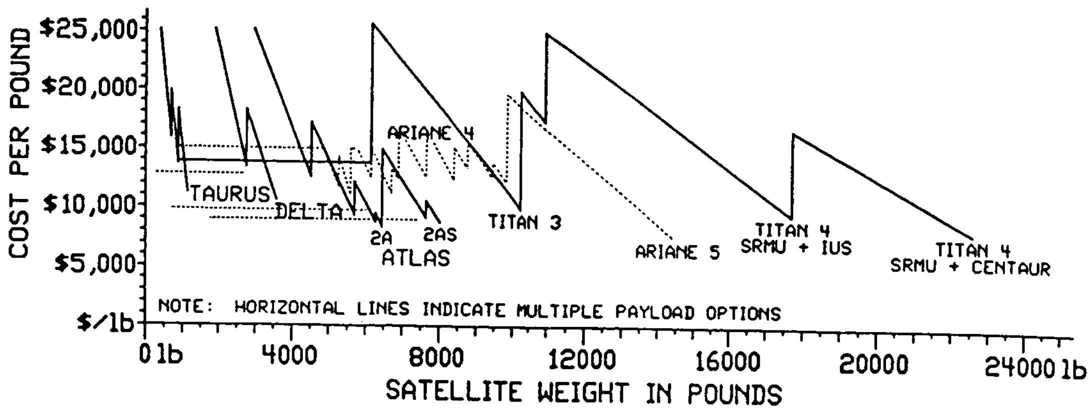

FIGURE 4. ARIANE VS. US LAUNCH VEHICLE COSTS

on the other hand, averaged more than 90% of the rated maximum payload.[24] The average launch costs for commercial satellites aboard U.S. launch vehicles was slightly greater than $17,500 per pound, whereas, Ariane dual payload launch costs averaged $15,600 with single payload launches averaging only $12,200.[25]

Ariane multiple payload configurations gives Ariane an excellent tool for keeping costs down for different sized payloads. Two different sized payloads, hat may cost considerably more on any other vehicle, can be matched to obtain a near full payload on an Ariane launch vehicle. Ariane's multiple payload capability and 16 different launch configurations provides the significant advantage of being able to launch almost any size satellite for a reasonable rate by maximizing the launch vehicle takeoff weight limits.

The Ariane launch site in Kourou, French Guiana, offers a 15% advantage over launches from the U.S. because Kourou is near the equator. The Ariane launch advantage should be factored out when comparing Ariane to U.S. launch vehicles. With a full load, rates as low as $7,500 for Atlas 2A, $9,300 for Delta II 7925, and $8,800 for Titan 3 could be obtained if the Ariane launch advantage is factored out, compared to Ariane's $12,000 per pound average for its sixteen configurations.

The third measure of performance: launch vehicle selection

Launch vehicle selections were reviewed for all of the commercial launches from 1988 to 1992, in order to identify basic selection criteria used by the satellite owners. Launch vehicle decisions made by satellite organizations were found to be primarily dependent on cost per pound rates offered by launch vehicle manufacturers. A number of basic pass-fail criteria was first considered before the decision was reduced down to one of cost. Reliability, warranty, accuracy of placement, stress on the payload, export restrictions, and launcher availability were some of the key pass-fail items that sometimes narrow down the choice of launch vehicles. A few exceptions to the lowest cost per pound selection were noted by some organizations and countries that had loyalties to particular manufacturers. China, France, Russia, and the U.S military have always used specific launch vehicle manufacturers within their own countries. Even a few international communications companies with worldwide ownership seemed to have launch vehicle manufacturer preferences that related to the ownership percentages. But, without a doubt, most launch vehicle selection decisions were based on cost per pound rates to deliver the payload to geostationary transfer orbit.

The fourth measure of performance: launch vehicle technology

The review of launch vehicle technology was divided into three areas: (1) engine efficiency, (2) payload-to-takeoff weight ratios, and (3) reliability. Engine performance criteria was identified as engine efficiency rated in specific impulse (Isp), which is a ratio of the amount of fuel consumed to maintain a particular engine thrust. The payload-to-takeoff weight ratio was identified as a performance characteristic to measure how much rocket mass was expended to deliver a payload to a geostationary transfer orbit.

Reliability is another performance characteristic that estimates the odds of the payload reaching the desired orbit.

Liquid engine performance ratings have not increased significantly in the last thirty years and all of the world's launch vehicle manufacturers seem to have the latest liquid engine technology. The 1960's Russian Proton engine is still the most efficient kerosene liquid engine and the 1970's Shuttle liquid hydrogen and oxygen main engine is the world's most efficient engine.[26] Solid propellent motor performance has been slowly improving and the Titan 4, SRMU solid propellent strap-on booster, is the world's most efficient. Ariane launch vehicles use conservatively rated engines that are less efficient than any of the U.S. engines. There seems to be little advantage in the type of engine used for launch vehicles because the cost-to-performance tradeoffs are not significantly different. The lower performance solid boosters are less expensive and the higher performance liquid engines are more expensive.

The payload-to-takeoff weight performance ratios were found to be a relative indicator of payload launch costs. Most geostationary transfer orbit launch vehicles expend 99% of the takeoff weight in reaching orbit (Figure 5). Generally, the lowest payload cost per pound launch vehicles were near the high end of the payload-to-takeoff weight ratios and the more expensive ones had low ratios. Launch vehicle takeoff weight brings out the seriousness of weight reduction programs because cost efficiencies must drive the performance ratings and not the other way around. The Atlas has the highest payload-to-takeoff weight ratio, 1.6%, of all the world's launch vehicles.[27] The Titan 4 with the SRMU solid strap-on boosters and the Centaur upper stage has a higher ratio than all of the Ariane configurations. The Delta is in the lower third, below Ariane.

Strange as it sounds, launch vehicle success rates had little influence on the vehicle selection process. Launch vehicle customers seemed to be very tolerant of companies that were experiencing temporary setbacks from failures. Even when launch companies were suffering from consecutive failures, the customers for the upcoming flights never withdrew their payloads from the launch manifest for a number of reasons: (1) a rescheduled flight on another launch vehicle would have delayed the launch for about two years, (2) contract penalties would have been costly, and (3) there was a high probability that the launch vehicle problem would be corrected before the next flight. For customers that unfortunately lost their payload to a launch vehicle failure, they typically collected a percentage of the satellite construction costs from flight insurance and were offered another free launch as part of the warranty.

The plan to regain U.S. commercial launch dominance

Ariane has only three technical advantages over the U.S. launch vehicle companies: (1) 16 different launch vehicle configurations, (2) multiple payload capability, and (3) a 15% energy advantage of launching from Kourou, which is near the equator. If these three advantages are factored out, then Atlas 1/2, Delta 2, and Titan 3 would all be significantly more cost effective than Ariane. President Clinton's basic space launch policy prohibiting large expenditures on new spacecraft and limiting the military to low-cost upgrades to existing launch vehicles provides enough funding to solve the U.S. space launch problem, but only if the funding is used to implement multiple launch capability, additional configurations, and a new launch facility near the equator. His suggested upgrades include such things as replacing hydraulics with electromechanical systems, using lighter-weight materials, and updating avionics and software.[28] Clinton's launch vehicle upgrades may lower the costs even more for military payloads, but they do not address any of the issues that would help the U.S. commercial launch organizations reclaim the commercial launch market. The military is only watching out for themselves by lowering the costs for their military payloads. They have not yet realized the importance of a healthy U.S. commercial launch program that will, in the long term, provide continued low cost access to space. The U.S. could reclaim their once-held lead in launching commercial satellites if upgrades to the existing launch vehicles included the multiple launch capability, additional configurations, and a new launch facility near the equator.

Recommendation 1

Fund a multiple payload option upgrade for the existing Atlas 1, 2, 2A, 2A Block 1, 2AS and 2AS Block 1 configurations in order to compete with Ariane 4 multiple launch capability. Also, fund a multiple payload option, four or more satellites, upgrade for the existing Titan 4, SRMU and Centaur configuration in order to compete with the Ariane 5 multiple launch capability.

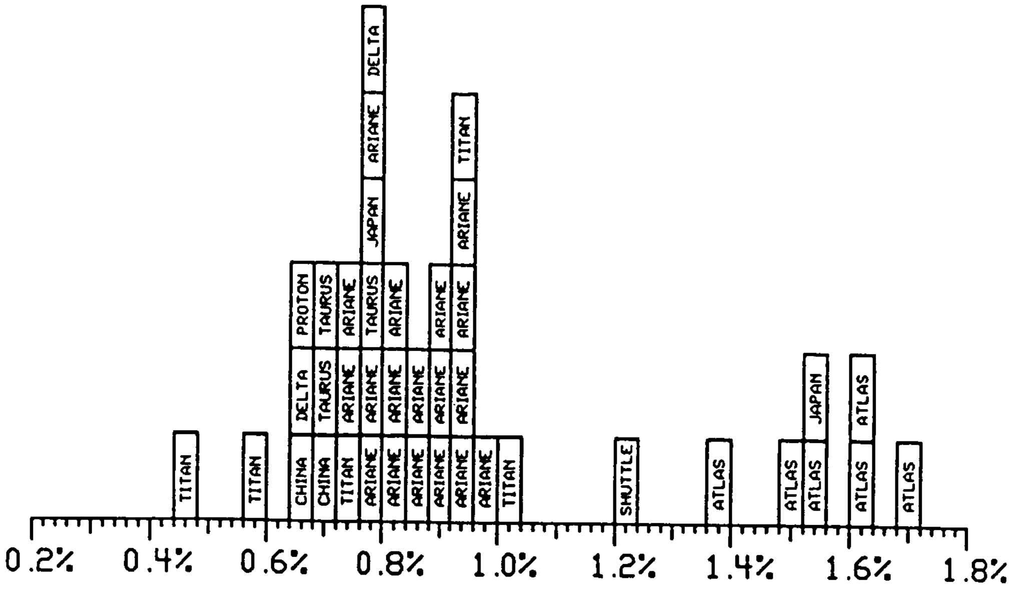

FIGURE 5. PAYLOAD-TO-TAKEOFF WEIGHT PERCENTAGES

The most important difference between Ariane and U.S. launch vehicles is Ariane's ability to launch multiple payloads. This one advantage is the key to understanding why Ariane now dominates the commercial launch market. U.S. launch vehicles had full load rates as low as $7,500 per pound for the Atlas 2A, $9,300 for the Delta II 7925, and $8,800 for Titan 3, but their average costs for commercial satellites were an incredibly high $17,500 per pound. Most of their launch vehicles flew with half empty cargo holds because they were not able to match payloads to optimize the payload capacities.

The military Titan 3 has the same payload capacity as the Ariane 4 and has been launching dual payloads for the military for over twenty years. The Titan 3 upgrades never kept up with increasing commercial payload sizes at economically competitive prices. The Titan 3 was designed to be both a low-Earth and a GTO launch vehicle with design efficiency emphasis on low-Earth orbit injection. Because of the low-Earth design emphasis, the second stage must go to low-Earth orbit before sending the last stage on to a geostationary transfer orbit, which makes the Titan 3 less efficient at sending payloads to geostationary orbit. The Atlas, on the other hand, is a perfect candidate for a multiple payload configuration upgrade. The Atlas is smaller than the Ariane 4, but could lure plenty of smaller payloads from Ariane. Ariane would then have a difficult time matching the larger payloads for multiple payload Ariane 4 and 5 configurations. Going after the smaller payloads is one way to regain part of the commercial launch market.

The Ariane 5, multiple launch configuration, will be capable of launching three satellites, which will provide a tremendous opportunity for Arianespace to match an even wider range of payloads to fill the spacecraft to its takeoff limit. Costs will be unbeatable unless the U.S. tops that with a Titan 4, SRMU and Centaur configuration, capable of launching four or more satellites to a geostationary transfer orbit. The Titan 4 also needs to be modified for a more efficient flight trajectory that would go directly to a geostationary transfer orbit instead of stopping at low-Earth orbit.

Recommendation 2

Fund economical launch vehicle upgrades to increase the number of launch configurations that widen the payload window while keeping the cost per pound rates low.

The second most significant technical advantage Ariane has is their ability to accommodate a wide variation of payload weights with their 16 different economical launch configurations. Any one of these configurations is available for use, whereas, U.S. launch companies are forced to phase out older configurations because they are no longer needed for military payloads. Every effort should be made to increase the number of usable launch configurations for Atlas, Delta, and Titan launch companies. Many military payloads. Every effort should be made to increase the number of usable launch configurations for Atlas, Delta, and Titan launch companies. Many different launch configurations are necessary to provide low cost rates over a wider range of payload weight.

Recommendation 3

The Department of Defense and commercial launch companies should build a launch facility near the equator to obtain a 15% savings in geostationary launch costs.

The third most significant advantage achieved by Ariane is their ability to launch from near the equator, which provides them with an immediate energy savings over comparable U.S. launch vehicles launched from Florida. A new U.S. launch facility would provide an immediate 15% cost savings for all flights to geostationary orbit. Ariane is not the only organization that will be taking advantage of the equatorial advantages, representatives from the Space Transportation Systems, Ltd., of Australia and four Russian enterprises have signed an exclusive 20 year $750 million contract for commercial equatorial launch services from Papua, New Guinea. The Russians claim the Proton can lift an additional 40% payload from the equator over their own northern Baikonur Cosmodrome launch facility.[29] The U.S. already owns two islands near the equator that could be used for a new U.S. launch facility. U.S. Baker Island and Howland Island, south of the Hawaiian Islands, are located closer to the equator than either New Guinea or Kourou. The initial investment would take many years to recover, but the advantages may make the difference for U.S. space launch survival.

Recommendation 4

Reduce the size and weight of future military satellites to be consistent with the size and weight of commercial satellites to benefit both the U.S. military and commercial launch sectors by providing common designs.

Military payloads have been designed to specifically carry out the intended mission regardless of the size and weight, which means that military payloads were seldom the same size and weight as commercial payloads. The Titan 3 was designed over thirty years ago and was capable of carrying military payloads that were many times the size of the largest commercial payload. The Titan 4 is also a very heavy lifter for its day and is capable of carrying more than twice the weight of today's largest commercial payloads. The size of military satellites needs to be scaled back to the same size of commercial satellites so that common spacecraft can be used for launching both military and commercial payloads.

Recommendation 5

Continue and encourage the split of military and civilian space launch programs in order to provide commercial sectors enough freedom to make competitive choices and react quickly enough to catch commercial opportunities.

Add a civilian contingent to the U.S. Space Command management structure and the Pentagon who would have the power and authority to influence decisions that concern commercial launch issues.

After "bench marking" Ariane and studying their performance strengths, a number of options have been uncovered that can be used to catch up and even surpass the success of Ariane. The survival of the U.S. commercial launch programs is in the hands of the Department of Defense until the commercial programs can become autonomous. Ground operations, launch facilities, and space policies are largely government controlled even though each of the three major launch companies (Atlas, Delta, and Titan) have their own commercial divisions and manufacture their own spacecraft. Too many military decisions are being made that have been detrimental to the future of the U.S. commercial launch business. Until commercial launch vehicle companies can break away from military entanglements, they will be unable to make the required competitive choices to ensure a future in the world's commercial launch market.

Conclusion

The U.S. commercial space launch program no longer dominates the world and is now playing "catch-up" with the world's first commercial launch company, Arianespace. The U.S. government created the space sector and must ensure a smooth and effective split from the emerging commercial space program in order to regain world dominance. Ariane, who is beginning to create their own world trade rules, is no longer tolerating subsidized launch vehicles. Until U.S. government and commercial ties are severed, the

Department of Defense must consider commercial space launch interests when making decisions.

Ariane has provided an excellent "bench mark" for the U.S. to base future launch vehicle upgrades. Ariane advantages were identified and low-cost recommendations have been made. If the U.S. sets the target of first equaling and then surpassing Ariane by incorporating these recommendations, then the U.S. could once again dominate the world commercial launch market.

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JUST IN TIME IN SPACE OR SPACE BASED JIT

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ABSTRACT:
Our satellite systems are mega-buck items. In today's cost conscious world, we need to reduce the overall costs of satellites if our space program is to survive. One way to accomplish this would be through on-orbit maintenance of parts on the orbiting craft. In order to accomplish maintenance at a low cost I advance the hypothesis of having parts and pieces (spares) waiting. Waiting in the sense of having something when you need it, or just-in-time. The JIT concept can actually be applied to space processes. Its definition has to be changed just enough to encompass the needs of space. Our space engineers tell us which parts and pieces the satellite systems might be needing once in orbit. These items are stored in space for the time of need and can be ready when they are needed -- or Space Based JIT. When a system has a problem, the repair facility is near by and through human or robotics intervention, it can be brought back into service. Through a JIT process, overall system costs could be reduced as standardization of parts is built into satellite systems to facilitate reduced numbers of parts being stored. Launch costs will be contained as fewer spare pieces need to be included in the launch vehicle and the space program will continue to thrive even in this era of reduced budgets. The concept of using an orbiting parts servicer and human or robotics maintenance/repair capabilities would extend satellite life-cycle and reduce system replacement launches. Reductions of this nature throughout the satellite program result in cost savings.

> What we did in the past, we do not want to do in the future.
> General Charles Horner 18 Sep 92

DISCUSSION:
The simple fact of distance has never been a real factor in material distribution--as long as you were still on earth. Getting a specific part when needed or within set time parameters became easier once the Just-In-Time (JIT) distribution concept was recognized and implemented. The JIT process is a material distribution concept plan where external suppliers deliver raw materials to the manufacturing facility just at the time the customer is ready to use those materials. As an internal continuation of the process, one department is pushing the product down the line just as the next department is ready to start using the product for their internal process. The JIT process has been proven to reduce costs when used properly. Storage costs are reduced, production time and costs are minimized and the overall manufacturing budgets are less. The work center is provided with the proper quantity of materials and components needed to do a given job at the exact time the materials are needed--or just in time.

Again, this concept is great, while you are on earth. One of the very first lessons learned from space travel had to do with planning what to bring along to assure you had what you needed when you needed it, or Space-Based JIT. It simply wasn't as easy in zero gravity to "space walk" over to the store for a missing part or that extra screw. We've learned our lessons well. Spares planning has become a very important aspect of every space mission: plan ahead for every eventuality, expect the failure and be ready for it. The concept of JIT needs to be expanded into the space arena. JIT needs to go beyond simple material distribution and enter a new, more complex dimension in space. The JIT distribution concept can work in space.

The integrated logistics support (ILS) elements (Figure 1) are the cornerstone for every project from conception to completion and concept of the replacement project. They cover 10 very important aspects of management functions through a disciplined, unified and iterative approach. While many logistics text books print the ILS elements in the order as shown in the referenced figure, I feel the last item on the list, Design Interface, is by far the most important of the 10. If not the first on the list, it should be the first logistical element in place following recognition of need. It needs to be the one element around which all the others revolve.

1. Maintenance Planning
2. Manpower and Personnel
3. Supply Support
4. Support Equipment
5. Technical Data
6. Training and Training Support
7. Computer Resources Support
8. Facilities
9. Packaging, Handling, Storage and Transportation
10. Design Interface

FIGURE 1. Integrated Logistics Support Elements

Design Interface considers and accepts or rejects aspects of initial conception and design. It includes necessary activities and training required for production. The design interface process integrates parts requirements into the overall picture throughout the life cycle. Design interface also addresses disposal or removal. Design interface is total support; total support of a system/project/idea covered through application of and processing through this one element. Supportability planning and related design considerations must be included in the requirements definition process and thoroughly evaluated during concept development to ensure options can be reasonably implemented in the operational system.[1] Design Interface will support our Space Based JIT concept.

The space program we envision today for our future will most likely be quite different from the one we actually put into place. Budget constraints and even public opinion will drive and change many of our plans and designs. It is likely that DOD will design high-value satellites, including potentially large constellations of strategic defense systems spacecraft for periodic revisit, servicing, and maintenance.[2] Even if the United States continues working in an international arena for space exploration, our share of the budget costs could be quite large. Controlling those costs creates a challenge for our space engineers. Getting down to the basics of controlling costs brings us back to another basic--designing for cost control, cost effectiveness throughout the system's life cycle. If space support is to be used routinely, the costs per mission for accessing space must be low. This extends to the costs associated with the vehicle, flight operations and the payloads.[3]

What we are doing today, both in terms of plans and actual building, will affect our entire program and shape our space future. What our engineers are creating in their minds today will be the driving force of budget problems tomorrow unless we show that changes in program strategy which include design constraints will not expose the overall program to unacceptable cost growth risks.[4] What we are developing in the face of budget constraints is very much dependent on our understanding of design interface. Our final designs, if they are going to work, must be specified in design-related terms that can be unambiguously interpreted, designed to and demonstrated.[5] In addition to working a design for cost considerations, more attention must be directed toward such design characteristics as reliability, maintainability, human factors and supportability.[6] What we are considering within today's budget figures must be supportable within the range of tomorrow's money, for throughout the design process, the key words to remember will be operability, manufacturability, supportability, availability and cost-effectiveness.[7]

Planning for the future through design has all of the ILS elements working as one within and across specific programs. Taking those lessons learned from our past space flights and applying them in the design of our future space programs is not only the smart way to go, it is the only way to go. We cannot continue designing spacecraft systems without incorporating supportability elements. Supportability refers to the design of a system such that it can be supported effectively and economically throughout its planned life cycle.[8] Even while trying to remain competitive with other companies, supportability of space assets must be programmed in so that those assets become and remain vital components of an overall space system. These ideas, if implemented on future space vehicles or during block upgrades to existing space systems could quickly produce the design, employment, and capability of on-orbit support.[9]

Designing in on-orbit support makes sense when you start looking at dollars and cents in light of handling tomorrow's budget. "Today, fully one-third of our space budget goes to maintaining the support infrastructure, buying and operating launch vehicles, maintaining and upgrading the launch infrastructure, sustaining the satellite control network...when you add to that one-third the cost of replenishing our current on-orbit capabilities, GPS, DSCS...you've captured about 70% of our space budget."[7] Between our communications satellites, weather birds, the family of navigational aids and the various intelligence groups, we've got alot of space assets out there in various orbits depending on the mission. Those assets are also in various stages of their respective life cycles. Logistics support problems increase with the age of the system and the rate of obsolescence of the technology employed in its manufacture.[5] Essentially, these space-based systems either directly or indirectly support all of our major military weapon systems. The capabilities and force enhancements provided by these systems are so important that extreme measures are taken to ensure their performance and survivability. Being able to access spacecraft on-orbit and perform servicing functions has the potential to increase performance, improve survivability and lower the total program cost.[4]

Our lessons learned have proved to us that on-orbit servicing is not only feasible, but practical. We've also learned that spacecraft lifetimes of a decade or more are achieved with servicing. Properly designed spacecraft can be upgraded in orbit and critical spacecraft replacement hardware must be factored into future programs.[4] The concept of on-orbit maintenance has been proven over and over again, but in all instances, it was performed through an extra vehicular activity (EVA) on a specific, previously defined problem. Some of the missions went well and were relatively easy; others required more effort and time. In all cases, the necessary parts were packaged and carried out to the repair site. While this has worked very well in the past, our thinking and our planning must become futuristic. The changing world events and an ever-shrinking defense budget strongly suggest that we must change the way we think about things and do things, especially in the logistics community.[10] Those persons involved with space programs need to include more thought processes in the design interface aspect of their programs. Constraints and limitations of funding, existing support structure, and manpower, they all must be addressed. The overall objectives of the concept development program must include more thoughts of integrating the future servicing possibility in the initial design.

Servicing is defined as any activity performed on-orbit to assemble, maintain, repair, resupply, upgrade, deploy, retrieve, or return various spacecraft and/or facilities.[11] Servicing, or on-orbit support, covers all activities required to keep the space asset alive and well. Servicing when the parts are readily available is easier and in the long run, can cost less. Planning for on-orbit support covers all activities before launch and brings the future closer through the JIT concept.

Planning for servicing requires more than just how many screwdrivers are needed. Knowing what is to be repaired will drive the kinds and numbers of tools required. The manned versus robotics servicing process will compel the engineers to be creative in their thinking. A robotics servicer can perform better than a human. Or can it? Certainly, that same robotics servicer can be placed in areas where it is not feasible for humans to be, but there are many other differences to consider. Once those differences are challenged and addressed, we can move forward in planning. The definition of servicing as defined above can be expanded to include not only the maintenance repair and resupply functions, but also replacement during scheduled or unscheduled servicing times.

Any on-orbit servicing capability must start with a specific number and type of tools and equipment to perform known tasks. This capability for servicing depends on many things, but proper equipment to perform the mission is paramount. How many times will it be necessary for the astronaut or the robotics servicer to return for a different size tool? How many tools must they carry? Tools fall into three basic categories--existing, current development and recommended future designs. Those existing are already in the EVA inventory, the current development are those that are funded or are in prototype and the recommended have not passed the drawing board ideas.[12] What we have and what we will have in the future are a quantifiable item that can be used over and over again. Battery replacement for many spacecraft is a frequent servicing requirement. Tools need to be standardized to cut down on numbers required for performing the multitude of tasks necessary. This would in turn benefit the entire program through lower costs, uniform interfaces and wider availability. Many existing tools were developed for specific tasks on specific spacecraft and many others were developed because of specific missions. A more universal set of tools which could be applied to servicing on all spacecraft would be desirable and would result in lower transportation costs and less EVA crew training.

Fuel/fluid replenishment is another aspect of servicing to consider. A major drawback with fuel/fluid replenishment is the standardization--or non-standardization--of the connectors in use in the various spacecraft families. In order to handle this type of servicing, it would be necessary to develop the necessary connectors and have a variety of them available for use. However, there are many spent craft that cannot be refueled because that capability was not designed into them. This design flaw has left us with basically one support concept and that is abandonment. We cannot do any space-based on-orbit servicing and in most cases, there is no fuel or not enough fuel left to bring the space asset back to earth. An empty fuel tank is certainly the most obvious life-limiter of our space assets.[7]

So, what's being done? Abandonment of a single satellite might be acceptable if that satellite has repaid its initial costs twice over, but the concept of abandonment of large and expensive satellites, such as Milstar, is counterproductive in a time of reduced budgets. Some space vehicles are outliving their expected lifetimes. This is great. Others are not. Perhaps the argument could be for abandonment of those systems, but is it reasonable and even prudent to abandon them? Our space engineers are limited only by their thinking. And their thinking is hampered by dwindling budgets. And yet, studies have shown that no technology breakthroughs are required to perform on-orbit servicing of space systems.[9] Many of the systems, if repaired while orbiting, could carry out their respective mission even though more advanced technology will be used on later vehicles. Most existing space assets can be serviced and future families of satellites can be designed for on-orbit servicing to include replacement of parts and replenishment of fuels/fluids. Some of these will be necessary with robotics equipment, but many can be accessed by humans. In either case, the space community must expand beyond today's designs and produce those families of future satellites which operate at the efficiency we expect and operate within budget constraints. Life-cycle costs and improved system effectiveness can be undertaken through standardization of those elements that are similar across system boundaries.

Those satellites that cannot be supported by human astronauts must be capable of accepting robotics intervention. That family of satellites that is beyond the reach of our human capability can still be serviced and maintained. But, by today's standards, we still can and must take care of what's out there with what we have - and without the standardization of tools and fuel/fluid connectors, our servicers (both human and machine) must carry an array of extra tools. This possibility will not always be acceptable.

Let's take a look at what we have and what we can do with it. The very idea of a storage unit is nothing new, but where do you put it and what do you put in it? There are certain orbits which can be used where an object that is orbiting will continue at that specific orbit almost indefinitely. These orbits can be used to hold that storage unit. There are five of these orbits, Libration Points, also known as Lagrangian points for Earth-Moon orbits as well as similar points for Sun-Earth, Sun-Venus, and Sun-Mars orbits. Two of these Lagrangian orbits in Earth-Moon location are very stable and require a minimum of energy for an orbiting storage unit--a parts servicer. A parts servicer is simply a vehicle that holds the various and assorted tools necessary for servicing those satellites within orbital reach. This parts servicer can be placed in a strategic position for easy access by any Orbital Maneuvering Vehicle (OMV). Many of the satellites we would want to service are out of human reach and would need to be serviced through robotics intervention. The robot that is being sent to perform the servicing can easily be attached to the OMV. The number of parts servicers needed would be based on orbits available and numbers of satellites easily reached within each orbit. Based on reliability predictions, the parts servicer would be outfitted with parts specific for those satellites to be serviced and planned satellites to be launched. Based on design interface, the parts servicer could be available and ready when needed or Space-Based JIT.

Just to prove a point, that of cost savings, look at some tables that represent launch costs for some specific vehicles. These vehicles were chosen as all launch into Low Earth Orbit (LEO), Geosynchronous Transfer Orbit (GTO) and Geostationary Earth Orbit (GEO). Their weight loads range from 1,420 kg on the smaller Delta Payload Assist Module (PAM) to 4,600 kg for the larger Titan IV.

	Unit Cost ($M) 1978	1984	1990	Cost/kg ($k/kg) 1990 GTO/GEO
Delta PAM	20	35	55	38.7 / N/A
Atlas G	31	50	72	30.5 / 54.6
Titan IV	73	96	264	22.0 / 57.4

Figure 2 Launch Costs History

Simple math of cost per kilogram times weight load produces the next figure.

Vehicle	Weight Load GTO/GEO	Launch Cost GTO/GEO
Delta PAM	1,420 / N/A	54,954 / N/A
Atlas G	2,364 / 1,330	72,102 / 72,618
Titan IV	12,000 / 4,600	264,000 / 264,040

Figure 3 Costs per Launch

As we look at the figures represented above, simple economics tells us that continual replacement of any satellite family is expensive. The 1990 figures are almost triple the 1978 figures and will very likely continue to increase even more. The more we can put into orbit at an acceptable, lowest-possible cost, the more efficiently our space program will operate. One or two launches of the parts servicer on a Delta PAM into Libration Points could hold down the weight on payloads put onto an Atlas G or a Titan IV by having repair parts already in orbit waiting. One or two launches of a Delta PAM carrying an on-orbit parts servicer saves a great deal of money when compared with the launch of a heavier vehicle carrying a replacement satellite that has no on-orbit capabilities.

As we think more about a parts servicer orbiting with assorted parts stored, waiting for the time when there is a need, the idea of design interface begins to take on a new dimension. We simply cannot be cost effective while we store six or eight of one type part for various satellites. We need to design in and enforce some sort of standard in order to reach the point where we need store only one or two parts at the most. Satellites need to be designed for refueling and the ports for each unit must be within certain standards to allow use of one or two couplers for the vast majority of them. The interface between modules and the other parts of the satellite could be unique to each satellite design if necessary, but appears to be a good candidate to become a standard. It would allow the stowage of orbital replacement units from more than one satellite in the parts servicer. Standardization becomes a primary means of lowering life cycle costs and providing improved system effectiveness.[12]

Space logistics must become an increasingly critical element of the planning, design, development, and operation of future space systems--both manned and unmanned. The complex new challenges to be introduced in the emerging field of modern space logistics demand early recognition and planning by those in the related disciplines, in order to provide effective solutions to problems affecting program goals accomplishment and affordability.[2] Space-Based JIT becomes a vital link between the life cycle prediction and the life cycle actuality. Budget constraints already make it more economical to consider repair vice replacement of assets. With some repair parts already in space, payloads would be smaller and launch costs would reflect the weight reduction. With design interface considered, future satellites--standardized satellite--would be launched into orbits where they can be reached by the parts servicer and serviced when needed to extend their expected lifetimes. All things considered, some standardization of space assets through design interface incorporates many issues beyond just design changes. The outcome of the design process concerning space support issues which eventually effect budgets far outweighs the problems caused by making no changes at all. Logistics support has taken on a new urgency when we consider the space arena and that urgency must be met if we are to be a vital part of the space world, in today's markets with today's money. Supportability has never seemed so critical, has never been so important until this time of ever-shrinking budgets, scarce resources and increasing demands made on the space asset. The support of a satellite system is vital, no matter the mission of that system. Our repair robot or astronaut must be able to have the proper equipment to do the best job possible and the time is coming when we will not be able to launch everything we need in one package. We must have the means to put some of the more frequently used parts in a place where they can be stored, waiting for use--Space Based JIT.

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SPACECRAFT AVAILABILITY ENHANCEMENT BY IN-FLIGHT TESTING OF SPARE PARTS

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Abstract

This paper describes an approach to improve availability by testing redundant parts at pre-determined intervals. The purpose of the testing is to detect non-functional back-up equipment and develop work-around measures or replacement spacecraft before a failure of the primary equipment reduces availability. The work reported here is an outgrowth of the NASA Space Network's program for the maintenance and replenishment of the Tracking and Data Relay Satellite System.

The approach is based on a standby factor and a cyclic stress factor. The standby factor accounts for the effects of adverse storage conditions encountered as part of the in-flight environment. The stress factor accounts for the effects of physical or thermal cycling due to the application of force or power that characterizes the operation or use of a component.

By the quantitative consideration of standby and cycling risks, a regular testing interval can be calculated - an interval for testing that furnishes information for availability planning but does not subject the spacecraft to undue risk. This paper includes quantitative solutions for appropriate testing intervals for equipment configurations and failure rates that are representative of a Tracking and Relay Data Satellite. The effect of a single test on the availability of certain equipment is also illustrated.

Nomenclature

A	availability of service
A_b	availability of back-up unit
A_p	availability of primary unit
C	cyclic test stress in λ-equivalent time
F	failure probability of service
F_b	failure probability of back-up unit
L	limitation on life of spacecraft
NTB	net testing benefit
Q	standby factor on failure rate
R	response time after failure
S	shortfall in service availability
t	time in future
t_f	time in flight
t_i	time interval for prediction
U_b	unavailability of back-up unit
Up	unavailabiltity of primary unit
U	unavailability of service
λ	failure rate of operating unit
α	scale parameter in Weibull formula
β	shape parameter in Weibull formula

I. Background

The NASA Space Network includes five geostationary Tracking and Data Relay Satellites (TDRSs) controlled by ground terminals located primarily at White Sands, New Mexico. The TDRSs, from their high orbits, can view almost the entire surface of Earth. Each TDRS relays commands from a ground terminal to user spacecraft in low earth orbit (LEO). Each TDRS also relays data and telemetry from user spacecraft to the ground terminal. User spacecraft benefit from the Space Network's ability to communicate between fixed ground facilities and rapidly moving spacecraft at almost any time, and at almost any location in LEO.

To ensure the continuity of Space Network services, NASA monitors the state of health of the TDRSs, plans for changes in user requirements, and replaces or supplements TDRSs as necessary. Constellation replenishment planning depends on accurate estimates of TDRS lives. TDRS lives are predicted by reliability models. These models perform Monte Carlo simulations of the failures of all components except those already known to have failed.

In most cases, a TDRS has a primary and a back-up component for each required function. Thus, except for the time required to identify a failure and activate the back-up component, most component failures do not reduce the availability of TDRS communication services. A partial or complete communication failure occurs only if both a primary component and its back-up components fail. Back-up components are either active (e.g., connected to live electrical circuits, and, as a result, warmer than their environments) or inactive but ready to be activated by an up-linked command to throw a switch.

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II. Approach

Availability Improvement by In-Flight Testing

The NASA Space Network's TDRS's are not normally subjected to in-flight testing of spare components because the tests involve risk and expense. In the absence of in-flight testing of a spare component, the availability of the component type in a redundant configuration depends on two factors. The first factor is the availability of the primary component. The present functionality of the primary component is assumed to be obvious because it is in use. However, the primary component is subject to the possibility of failure at any future time. If its failure rate λ (often obtained by using MIL-HDBK 217[1]) is constant, then its availability A_p after a time interval t_i is:

$$A_p = e^{-\lambda t_i} \qquad (1)$$

and its unavailability is the complement of the availability, i.e.:

$$U_p = 1 - e^{-\lambda t_i} \qquad (2)$$

The second factor is the availability of the back-up component. The back-up component, or its switching circuit, could be in a failure state that will not be apparent until the item is switched on or otherwise placed in active service. Its exposure to environmental factors such launch acceleration and vibration, vacuum with out-gassing, ionizing radiation, and thermal cycling could have been responsible for its latent failure state. Alternatively, the passage of time alone could be responsible for its internally generated physical or chemical degradation to a latent failure state. The availability A_b depends on the standby factor Q multiplied by the failure rate λ, and on the accumulated time in flight (since checkout) t_f:

$$A_b = e^{-Q\lambda t_f} \qquad (3)$$

and the unavailability is the complement of the availability, i.e.:

$$U_b = 1 - e^{-Q\lambda t_f} \qquad (4)$$

The overall risk of unavailability U is the product of the two factors:

$$U = U_p U_b \qquad (5)$$

Substitution gives:

$$U = (1 - e^{-\lambda t_i})(1 - e^{-Q\lambda \tau_f}) \qquad (6)$$

The overall availability for the case without in-flight testing is the complement of the unavailability:

$$A = 1 - (1 - e^{-\lambda t_i})(1 - e^{-Q\lambda t_f}) \qquad (7)$$

If in-flight testing is under consideration, the predictive time interval t_i between tests should not exceed the time required for the implementation of alternative back-up or work-around measures. Furthermore, the accumulated time in flight t_f should not exceed the time required for the completion of the spacecraft's mission. In the meantime, there is an expected value for the shortfall S in spacecraft-years of service availability, depending on the time R required to respond to the failure:

$$S = U R \qquad (8)$$

Substitution gives:

$$S = (1 - e^{-\lambda t_i})(1 - e^{-Q\lambda t_f}) R \qquad (9)$$

Risk of In-Flight Testing

In-flight testing of a spare component could result in a failure because of the cyclic stress due to each test itself. The stress can affect the switch that applies power to the spare, the switch that connects the spare to other devices, and the spare equipment itself, but these phenomena are treated together for the purposes of this paper. If we assume that the cyclic stress C is given in l-equivalent hours of failure risk per in-flight test, then the failure risk to the spare component due to each test is:

$$F_b = 1 - e^{-\lambda C} \qquad (10)$$

Since the overall risk results from the failures of both the primary and the back-up components, the expected value of failed spacecraft-years F in terms of potential spacecraft life (since launch) L is:

$$F = U_a Fb \qquad (11)$$

Substitution gives:

$$F = (1 - e^{-\lambda t_i})(1 - e^{-\lambda C})(L - t_f) \qquad (12)$$

Appropriate Testing Intervals

In-flight testing of a back-up component could be beneficial if the shortfall S in spacecraft service expected during the failure response period is significantly greater than the testing stress failure expectation F. The in-flight testing of spare components would not prevent any failures, but it could facilitate operational planning to maintain service and to obtain value from the programs being served. TDRS services are believed to be much more valuable than TDRS costs, because the services are needed by many user spacecraft that may greatly exceed TDRS in cost and value - but only if a TDRS can return their data. TDRS user spacecraft programs include the following:

AXAF	Advanced X-Ray Astrophysics Facility
COBE	Cosmic Background Explorer
EOS	Earth Observing System
ERBS	Earth Radiation Budget Satellite
EUVE	Extreme Ultraviolet Explorer
GRO	Gamma Ray Observatory
HST	Hubble Space Telescope
ISSA	International Space Station Alpha
LSAT	Landsat
SS	Space Shuttle
TOPEX	Ocean Topography Experiment
TRMM	Tropical Rainfall Measuring Mission
UARS	Upper Atmospheric Research Satellite
XTE	X-Ray Timing Explorer

Furthermore, in-flight testing of spare components could enable expensive and time-consuming procurements of replacement spacecraft to be either accelerated or delayed, whichever may be appropriate, depending on the functionality of the in-flight equipment.

For these reasons, advanced knowledge and prevention of potential spacecraft service shortfalls could have value comparable to, or greater than, the spacecraft themselves. Assuming that the values of S and F are comparable directly, the net testing benefit NTB in spacecraft-years can be defined for any test event as:

$$NTB = S - F \qquad (13)$$

Substitution gives:

$$NTB = (1 - e^{-\lambda t_i})(1 - e^{-Q\lambda\tau_f}) R - (1 - e^{-\lambda t_i})(1 - e^{-\lambda C})(L - t_f) \qquad (14)$$

For application to a periodic testing program, the NTB must be summed over the life of the spacecraft. Note that small testing intervals may not be practical if they result in cycling that approaches or exceeds the finite life of a component, which is not considered in the above constant failure rate-based equations. Also note that the implementation of small testing intervals could be costly, reducing the NTB.

III. Examples

Cyclic Stress and Testing Interval

The first example illustrates the determination of an appropriate testing interval. The numerical values used here are typical of many TDRS components that are configured with an active primary unit and an inactive back-up unit that is switched on if and when it is needed. A typical failure rate λ for the active component is one failure per million hours and the standby factor Q for the back-up component is 0.1, in accordance with standard failure rate data[1] and project documents[2-4]. The response time R (based on the highly variable average time to build and launch a replacement spacecraft) is estimated at three years, and the lifetime L of a spacecraft is estimated at 15 years (also an uncertain estimate, probably by plus or minus five years). On the basis of the above formulas used in spreadsheet calculations, the testing interval t_i that maximized the net testing benefit NTB was evaluated as a function of cycling stress C in λ–equivalent hours (see Figure 1).

For low values of cyclic stress, the test interval is about one month. As cyclic stress increases to about 2000 hours, the testing interval increases to about one year. At higher cyclic stresses, the testing interval continues to increase, indicating that testing may not be appropriate. It may therefore appear that cyclic stress needs to be determined before choosing a testing interval. However, this probably is not the case. The reason is that the net testing benefit for the entire range of cyclic stress is only about 0.001 spacecraft-years. This NTB appears to be too small to justify a testing program.

Cyclic Stress and Net Testing Benefit

The second example involves a component configuration in which the back-up equipment is active (e.g., connected to live electrical power supplies) but its functionality is not known until it is switched into actual use. An example is the transponder in TDRS's tracking, telemetry, and command (TT&C) subsystem (though a small fraction of the back-up equipment is not active). Numerical values are the same as in the first example, except that the failure rate λ is one failure per 100,000 hours and the standby factor Q is 1.0. These higher values greatly increase the net testing benefit. The testing interval that maximizes the NTB is determined to be about two months, independent of cycling stress. However, the NTB does depend on cycling stress (see Figure 2).

In this example, the cyclic stress must be known, not to determine test interval (which is about two months for all cyclic stresses shown), but to determine whether testing is beneficial. However, because the back-up unit is powered continuously whether tested or not, the stress of testing appears to be small, almost certainly less than 1,000 hours based on the author's subjective estimate. Therefore, testing appears to be beneficial by affording an expected value of almost two years of notice of an impending failure. For comparison, the expected value of additional spacecraft failure-years attributed to the testing is less than 0.1 years.

Spacecraft Reliability and Useful Life

The third example involves TDRS 1, which was launched on April 4, 1983, and, at an age of about 12 years, is operating beyond its design life. There has been no testing program for the TT&C transponder on TDRS 1. Therefore, the back-up transponder's functionality is not known. According to a MIL-HDBK 217D-based, parts-count, Monte Carlo reliability model shown here only schematically (see Figure 3), if the back-up transponder were to be tested successfully, the prospects for the life of TDRS 1 transponder functionality would improve markedly (see Figure 4).

With no test, the predicted availability of the TDRS 1 TT&C transponder fits a two-parameter Weibull formula:

$$A = e^{-(t/\alpha)^{\beta}} \qquad (15)$$

in which the scale parameter α is 18 years and the shape parameter β is 1.23. The future time t is limited to eight years because by then the satellite will be at the approximate limit of its foreseeable useful total life of about 20 years. The nearness of the shape parameter to unity indicates that the 12 year old back-up equipment is probably no longer fully functional. The mean remaining life of the TDRS 1 TT&C transponder is 6.8 years.

If a test is performed and shows that the back-up equipment is fully functional, α would increase to 23 years, indicating that the life of the transponder is likely to be longer, and β would increase to 1.64, a value that indicates the presence of redundancy. The mean remaining life of the TDRS 1 TT&C transponder would increase to 7.5 years.

However, if the test is performed and shows that the back-up equipment is non-functional, α would decrease to 11 years, indicating that the life of the transponder is likely to be shorter, and β would decrease to 1.00, a value that indicates the absence of redundancy. The mean remaining life of the TDRS 1 TT&C transponder would decrease to 5.6 years.

IV. Conclusions

The in-flight testing of spare components, while increasing rather than reducing failures, could be beneficial if the knowledge of back-up functionality were used to prepare and implement responses to impending failures. However, as shown by the first example in this paper, the testing would not be appropriate for most back-up components on TDRS, because their estimated failure rates are too low to produce a significant benefit. This result is consistent with the NASA Space Network practice of not normally performing in-flight testing of spare TDRS components.

In some cases, the in-flight testing could be appropriate. These cases can be identified by their high estimated failure rates for both the primary and the back-up components. The most likely candidate on a TDRS appears to be the TT&C transponder. Of course, the type of screening analysis shown in this paper is not sufficient to warrant the implementation of an in-flight testing program for the transponder. Failure rates, failure modes, standby factors, cyclic stresses, wearout phenomena, and the likelihood of test results affecting future operations or procurements would all require more detailed evaluations before deciding on whether to test in-flight. For example, the historical TDRS TT&C transponder failure rate appears to have been lower than the MIL-HDBK 217D rate, and a reduction in the rate would reduce the net benefit of testing. Nevertheless, further evaluation of the possibility of in-flight testing appears to be worthwhile.

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Fig. 1. Testing Interval to Maximize Net Testing Benefit (Years)

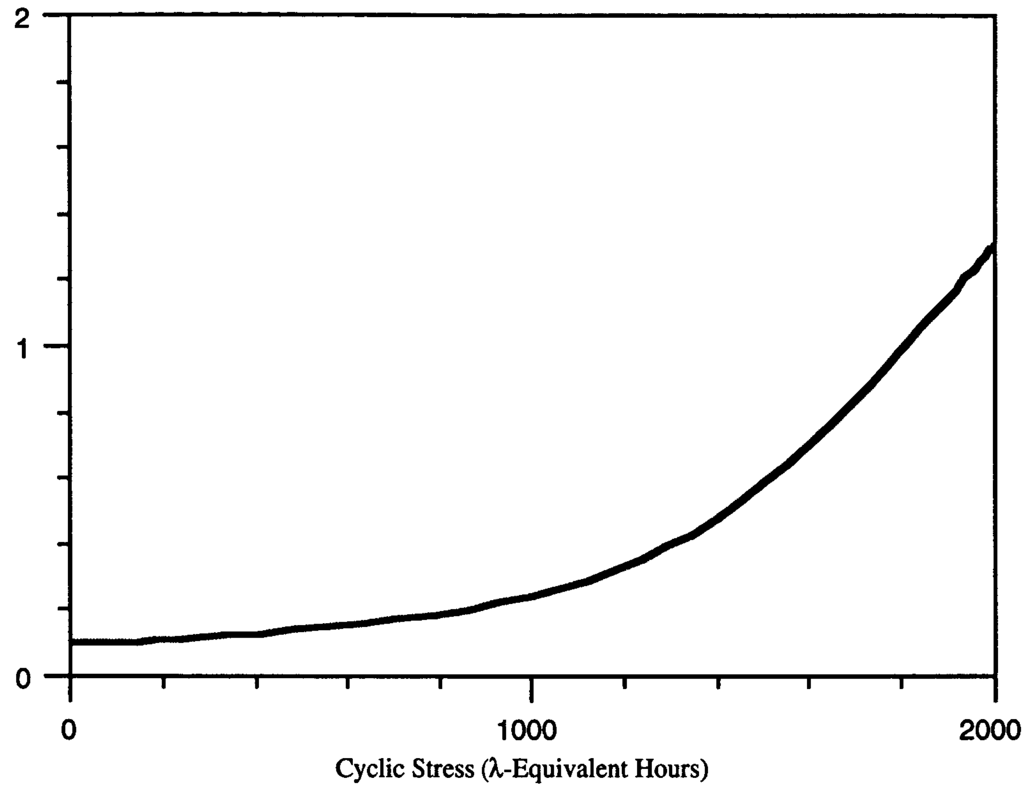


Fig. 2. Net Test Benefit (Spacecraft-Years)

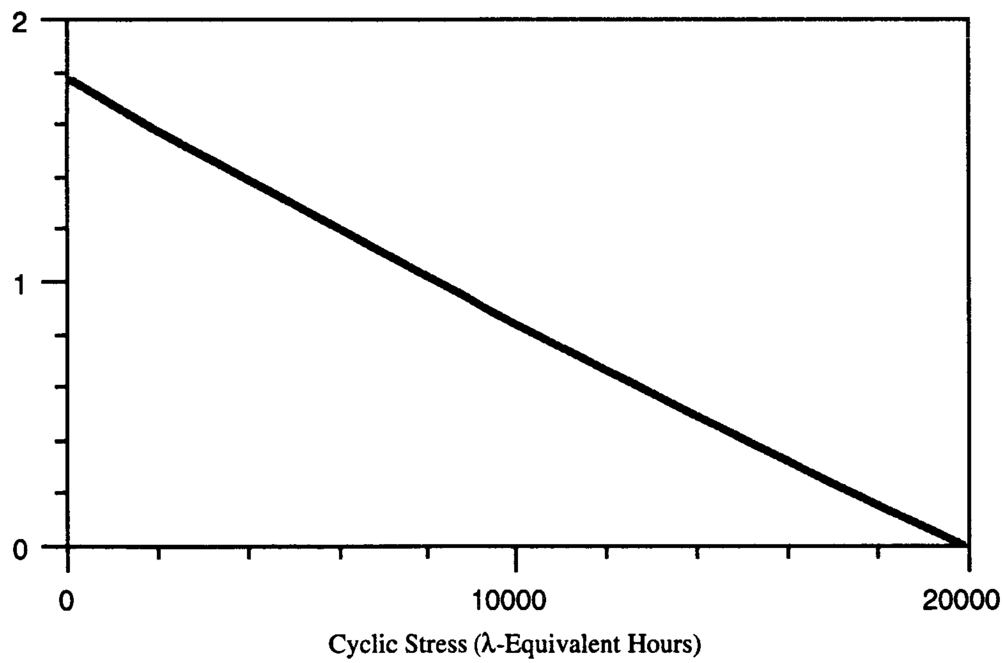


Fig. 3. Schematic Diagram of TDRS TT&C Transponder

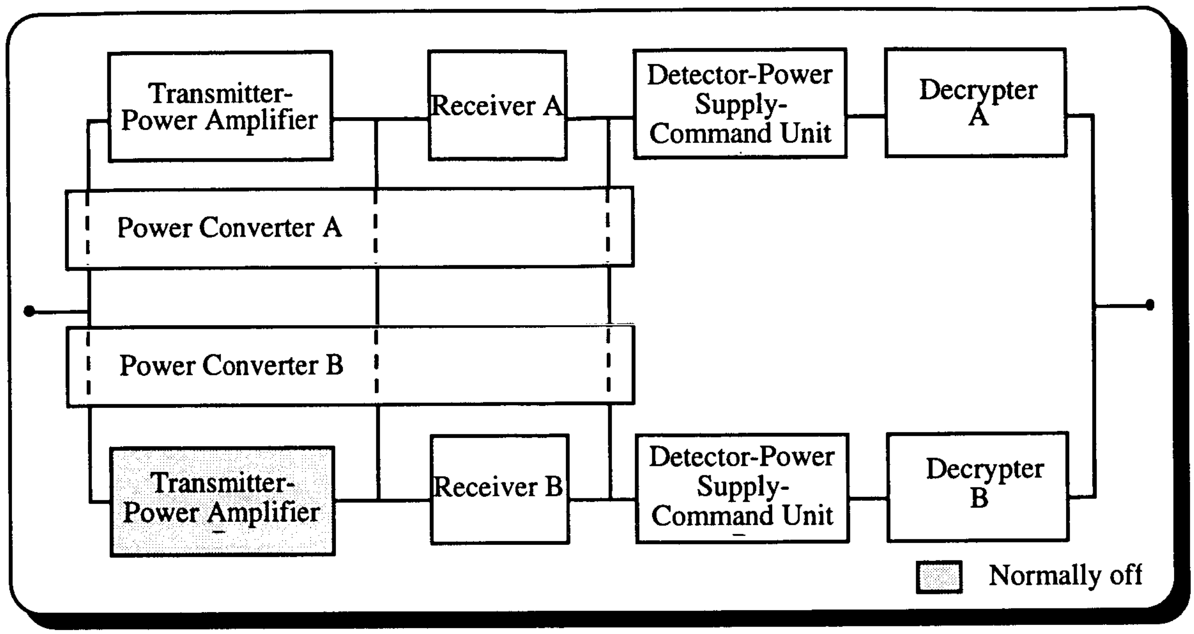
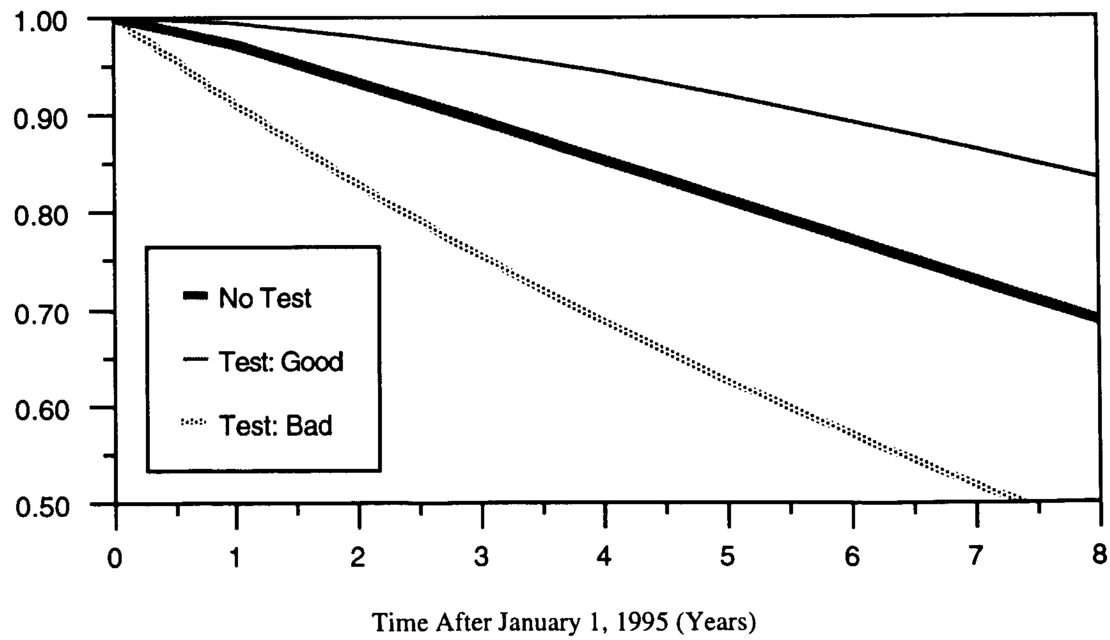


Fig. 4. Reliability of TDRS 1 TT&C Transponder



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EFFECTIVE TRANSITION MANAGEMENT
THE SEAMLESS SYSTEM

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Introduction

In this age of shrinking resources, cost avoidance has become as critical as direct cost savings. There is no doubt that Effective Transition Management achieves this aim.

What then, is Effective Transition Management and how does it achieve its goal? It is the introduction and use of a hierarchical decision model and computerized tracking system which successfully integrates capital acquisition into the support base. You will discover that because this proven system is generic, compatible and flexible, its applications are virtually unlimited. It is this highly dynamic process which I would like to share with you.

Skilled specialists are now rotated rapidly through acquisition programs on a requirements-driven basis. Managers continue their quest for inefficient areas to trim, slash or cut. However, there is one area of operations in every major corporation and government department that, as yet, has not received the attention it deserves. This essential element is Transition Management.

Capital acquisitions, at some point, must be handed-off to a support matrix for the "in-service" phase of their life cycle. Most of us who have been on the receiving end can usually cite outrageous examples of adjustment, recovery or disaster. This means buying what amounts to a second initial sparing package, re-aligning the range and depth of inventory to match a changed maintenance concept, interpreting contractor-developed configuration control data or ensuring that the latest information is contained in the technical publications. This list is endless. For major purchases, this "in-service" phase is often fifteen, twenty or more years. The least desir\able, yet most common condition, is to suffer up to five years of recovering from errors or omissions after the transition to the support matrix occurs. Without Effective Transition Management, making new equipment fully operational may thus become a long and costly process.

Scope

This process applies to any organization which is buying capital equipment and which is then required to maintain the support of that equipment during its ensuing in-service life cycle.

Concept

The concept of Effective Transition Management has two objectives. The first is the identification of resources and timings to facilitate the long range planning and programming. The second is the development of a check list and procedures to smoothly execute the transition of the capital equipment systems management responsibilities from the Program/ Project Manager to the lead Matrix Support Manager.

A Transition Plan should be prepared at the earliest possible date in the life of the project, usually two years before the transfer is scheduled to take place and must be approved by senior management. Normally, the transfer will be for complete systems. However, in certain instances, a system may be introduced by components, in which case the plan should follow a phased approach. As above, the Transition Plan for the first component will normally be prepared at least 24 months before it is transferred to the lead Matrix Support Manager.

> **CONCEPT**
>
> - **IDENTIFY RESOURCES AND TIMINGS FOR LONG RANGE PLANNING**
> - **DEVELOP CHECKLIST AND PROCEDURES TO EXECUTE SMOOTH TRANSITION**

Definition of Terms

1. Transition Plan (TP).

   - The document which outlines actions, responsibilities and agreements relative to transferring systems management from the program/project to the support matrix. It contains a schedule of events for an orderly and timely transfer of systems management responsibilities and addresses resource implications. Senior management will normally approve the Transition Plan.

2. Transition Plan Steering Committee (TPSC).

   - The TPSC is a decision level group comprised of the Program/Project Manager and key Support Managers or their representatives involved in the introduction and support of the newly acquired system.

3. Transition Plan Working Group (TPWG).

   - The TPWG is a Working Group of program/project and matrix representatives whose responsibilities include developing the Transition Plan detail and executing the detailed transition activities. Membership, as a minimum, will include the losing and gaining managers. The size and scope of the TPWG will depend upon the size and complexity of the program/project. Lead responsibility lies with the Program/Project Manager. In general, the chairmanship of the TPWG is delegated to the project's Integrated Logistics Support (ILS) Manager and the gaining lead Matrix Support Group's Transition Manager becomes the deputy of the TPWG. Members of the TPWG are those who are designated as support staffs and subject matter experts of the various related activities usually listed in an Implementation Plan.

4. Transition Manager.

   - The Transition Manager is the individual, nominated by the lead gaining Matrix Support Manager and approved by senior management, responsible to ensure that Transition Plans prepared for the system(s) to be handed over to the in-service support matrix are successfully concluded.

5. Matrix Manager.

   - A Matrix Manager is an individual in the fixed array with cognizance for the staff and area of expertise that the program/project office draws upon to carry out its responsibilities.

6. Senior Review Board (SRB).

   - A senior decision-making body normally chaired by the senior manager and comprised of permanent core members determined by areas of responsibility.

7. Master Transition Agreement and Schedule (MTAS)

- The coordinating schedule for identifying the losing and gaining managers, equipment transition dates, and resource impacts, as well as all agreements between gaining and losing organizations. The MTAS is a living document agreed to by all levels of management up to the SRB or senior manager as applicable. It will be published semi-annually or more frequently, as required.

Applications

The transition of each system or major component will be tailored to the level of management required and the ability of the gaining organization to assume system responsibility. If the prime equipment exists or if there is an association with existing equipment already being managed, the new system or component shall go to the office with the equipment unless otherwise directed by the SRB.

APPLICATIONS

- **TAILORED TO LEVEL OF MANAGEMENT REQUIRED**
- **ABILITY OF GAINING ORGANIZATION TO ASSUME SYSTEM RESPONSIBILITY**
- **NEW SYSTEM NORMALLY DESIGNATED FOR OFFICE WITH EXISTING EQUIPMENT**

Formal Organization

Transition Planning is based on the efforts of two organizations, the Transition Planning Steering Committee (TPSC) and the Transition Planning Working Group (TPWG) which may entail ancillary TPWG Sub-Working Groups. Figure 1 illustrates their relationship to the Senior Review Board (SRB).

The TPSC is normally formed at least two years prior to the required transition date. The TPSC consists of the Program/Project Manager and key support managers or their representatives from all the areas of responsibility involved with the Materiel Management of the system being introduced.

The TPSC's function is to oversee the transition of the Materiel Management of the system to the in-service support matrix. Subordinate to the Steering Committee is the Working Group consisting of a Chairman (the Program/Project ILS Manager), a Deputy (the Transition Manager), a Secretary (a designated Working Group member), regular members (pertinent support staffs) and ad hoc members (representing all subject matter experts in areas addressed in the Implementation Plan on a consultative basis).
Sub-Working Groups will be formed by the TPWG on an as required basis. The membership will be representative of the subject matter under consideration.

Responsibilities of the Groups

The losing and gaining managers are jointly responsible for system/ component transition. Each transition will occur at an agreed-upon date and under agreed-upon conditions. The overriding factor is that the operational management of the existing system(s) will not be adversely affected as a result of a system or component in transition.

A Transition Manager will normally be appointed by the gaining Life Cycle Management component. However, other options are either to establish a position in the capital project when the personnel requirements are being identified and staffed, or utilize an appropriate program/project manager who is intended to move to the managing component when the program/project is complete. The term Transition Manager may or may not include other staff which will be determined by the level of effort required. When the prime contract has been signed, the Transition Manager will likely reside in the program/project management office. The Transition Manager will remain there until the major share of the Transition Plan has been completed.

RESPONSIBILITIES

- **JOINT**
- **AGREED CONDITIONS**
- **MAINTAIN OPERATIONS MANAGEMENT READINESS**

Functioning

The chairmanship of the Steering Committee is the joint responsibility of the Program/Project Manager and the lead Matrix Support Manager (co-chaired). The Steering Committee reports to the SRB through the Program/Project Manager.

In the TPWG, each Sub-Working Group (SWG) Chairman provides a monthly written progress report to the Working Group Chairman. These reports are normally reviewed by the Transition Manager. From these reports and the TPWG meetings, the Working Group Chairman brings forward to the Steering Committee any unresolved item(s) considered beyond the scope/authority of the Working Group and provides regular updates on the progress of the Working Group.

The TPSC is intended to be few in numbers yet have enough authority to make most decisions without seeking the approval of higher management. Members are chosen from areas considered vital to the success of the transition; ie the Program/Project Manager, the lead Matrix Support Manager and other relevant matrix support managers. The Chairman of the Working Group, on the other hand, is mandated much narrower parameters of autonomy and authority. Progress is to be reported to the Steering Committee and action is to be agreed to by the Steering Committee. The TPSC is a decision-making body which chooses between alternatives presented by the TPWG and investigates the broader policy implications. If the proposed solutions exceed their authority, the Program/Project Manager is responsible for presenting agreed upon options to the SRB. The TPSC is co-chaired by the Program/Project Manager and the lead gaining Matrix Support Manager.

The TPWG is charged with preparing and implementing the Transition Plan. The TPWG is responsible for identifying the areas that require investigation and setting up the Sub-Working Group(s) to carry out the investigation. If the proposed solutions can be implemented by the TPWG no further action is required except to inform the TPSC. If not, the problem is passed to the TPSC for resolution. The TPWG is normally chaired by the project ILS Manager with the Transition Manager as deputy.

The TPSC should hold a meeting at least every six months (more frequently depending on activity). There will normally be two Working Group meetings for every TPSC meeting. Sub-Working Group (SWG) meetings are less formal and more frequent. Each SWG Chairman provides a monthly written progress report to the Working Group Chairman through the Transition Manager. The Working Group Chairman will bring forward to the TPSC any unresolved items(s) considered beyond the scope/authority of the Working Group and provides regular updates on the progress of the Working Group.

The format used at the TPSC meetings will be to review previous minutes and be updated by the TPWG Chairman on the progress of the Transition Plan. This is to be followed by the tabling of unresolved items with available options for discussion and resolution/decision by the TPSC.

The established governance structure at Figure 1 will be used to escalate unresolved items for direction/arbitration where required.

The Transition Plan is deemed to be approved once all members have signed off and the presentation has been accepted by SRB or the applicable senior manager.

The Master Transition Agreement and Schedule (MTAS) should be revised every six months or more frequently as directed.

Contents of the Transition Plan

The following is a list of the major elements and reports (examples given illustrate an imaginary status as of Dec 4, 2000) in the Transition Plan:

- the Transition Plan Data Flow (Figure 2);
- a recommended list of Transition Plan Work Packages from the Work Breakdown Structure;
- the MTAS report for the complete system to be transitioned showing by percentage those Work Packages remaining incomplete and those already 100% completed. This provides an overview of the project's current status at a glance;
- a second report showing only the incomplete Work Packages remaining to complete the transition;
- a breakdown by functional group within the project of progress-to-date and an average percentage completed;
- a third report providing a breakdown of all incomplete tasks by functional group and an average percentage completed;
- the "*key*" graph which illustrates current System Transition Progress. This graph is produced automatically when linked to the database. When the database is posted up-to-date, a graph may be produced showing Management at a quick glance, the status of the project, equipment system, subsystem, or component, depending on the data kept in the database; (Figure 3 - "a picture is worth a thousand words");
- each task may be subdivided into as many subtasks and sublevels as management considers necessary;
- an iterative process may be used; and
- a suggested handover document to be used when the transition is completed.

Additional information may be tracked by expanding tasks at the subtask level, for example:

- financial assistance required by line organizations involved in the transition process;
- training required by the matrix and the lead time necessary to get that training;
- short/long term manpower/ funding required by the matrix;
- tools and test equipment in an automated environment required to manage the in-service life cycle phase;
- maintenance of warranties and the follow-on buys that are a continuation of the same system;
- publications to be transferred such as: specifications, independent evaluation plans, results of any trials/test including the raw data, and the management of the database and selection of tools required for its life cycle management;
- maintenance and tracking of engineering change proposals, design change proposals and failure reports to be transferred to the matrix life cycle managers; and
- lastly, initiation of the replacement system and necessary studies, if required.

Note:

Due to individual requirements of each project, this is not meant to be an exhaustive list but only to highlight the main tasking areas which most programs/projects must address.

Responsibilities of the Transition Manager

The Transition Manager must be responsible to ensure that Transition Plans prepared for system(s) to be handed over to the in-service support matrix are successfully concluded:

TRANSITION MANAGER

- **NORMALLY FROM LEAD MAINTENANCE ORGANIZATION**
- **ENSURES PLANS PREPARED**
- **BRINGS TRANSITION TO SUCCESSFUL CONCLUSION**

- by developing, maintaining and controlling the overall time line transition schedule;
- by assuring that all transition issues are brought to a successfull conclusion.

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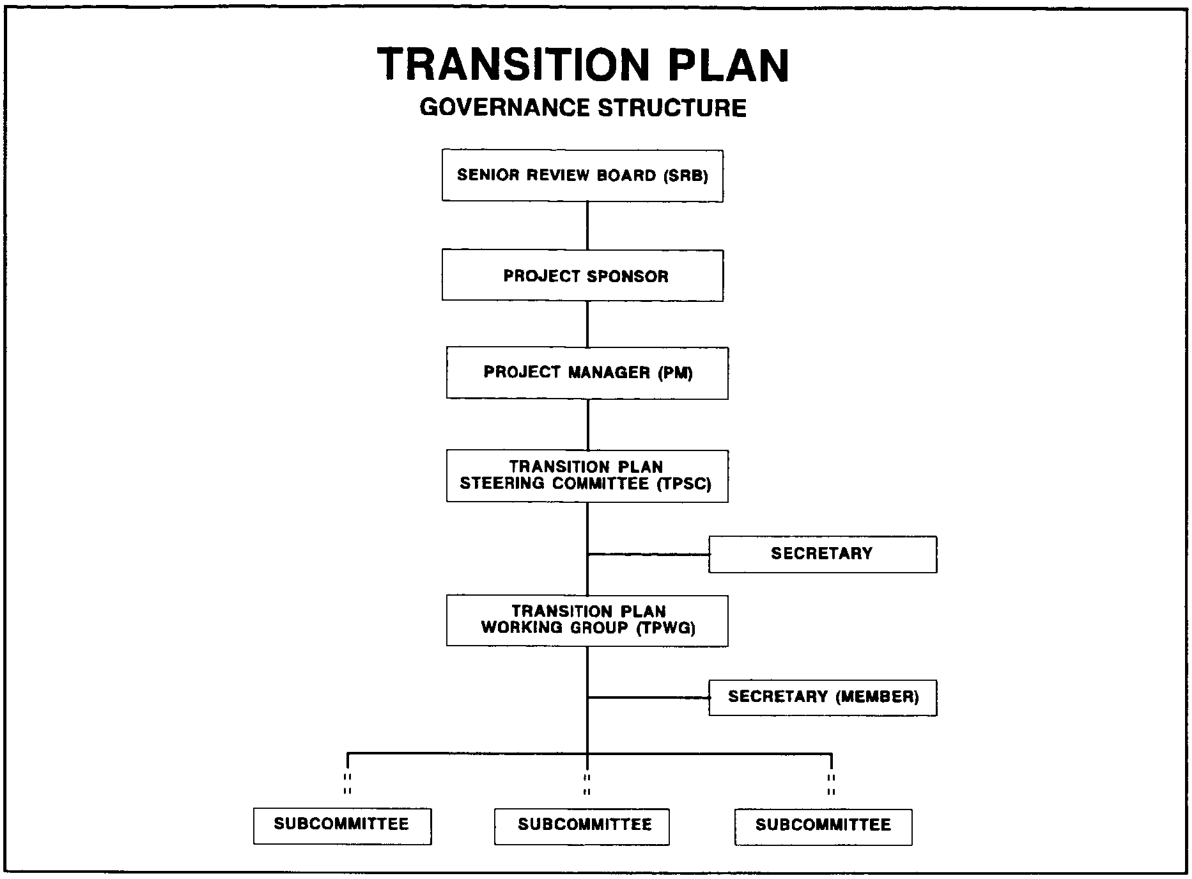

Figure 1 Transition Plan -- Governance Structure

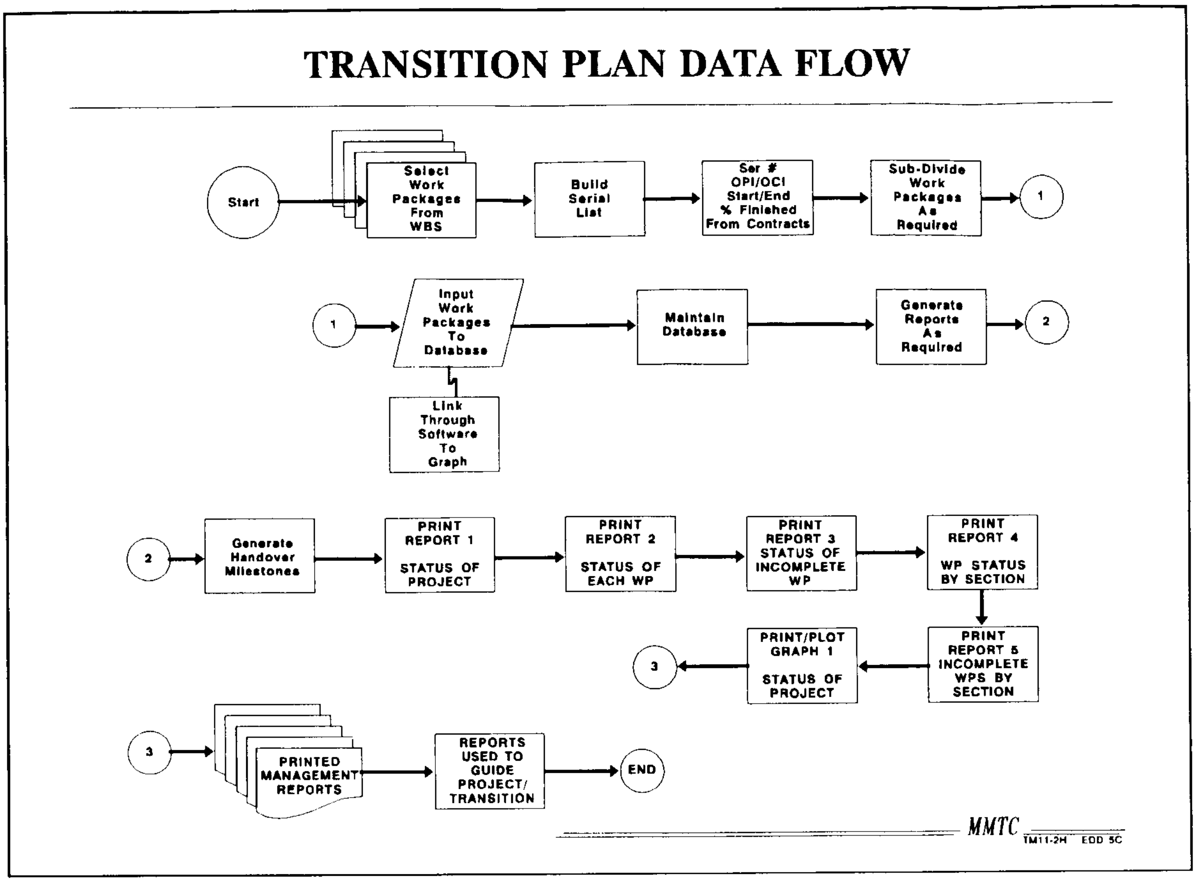

Figure 2 Transition Plan Data Flow

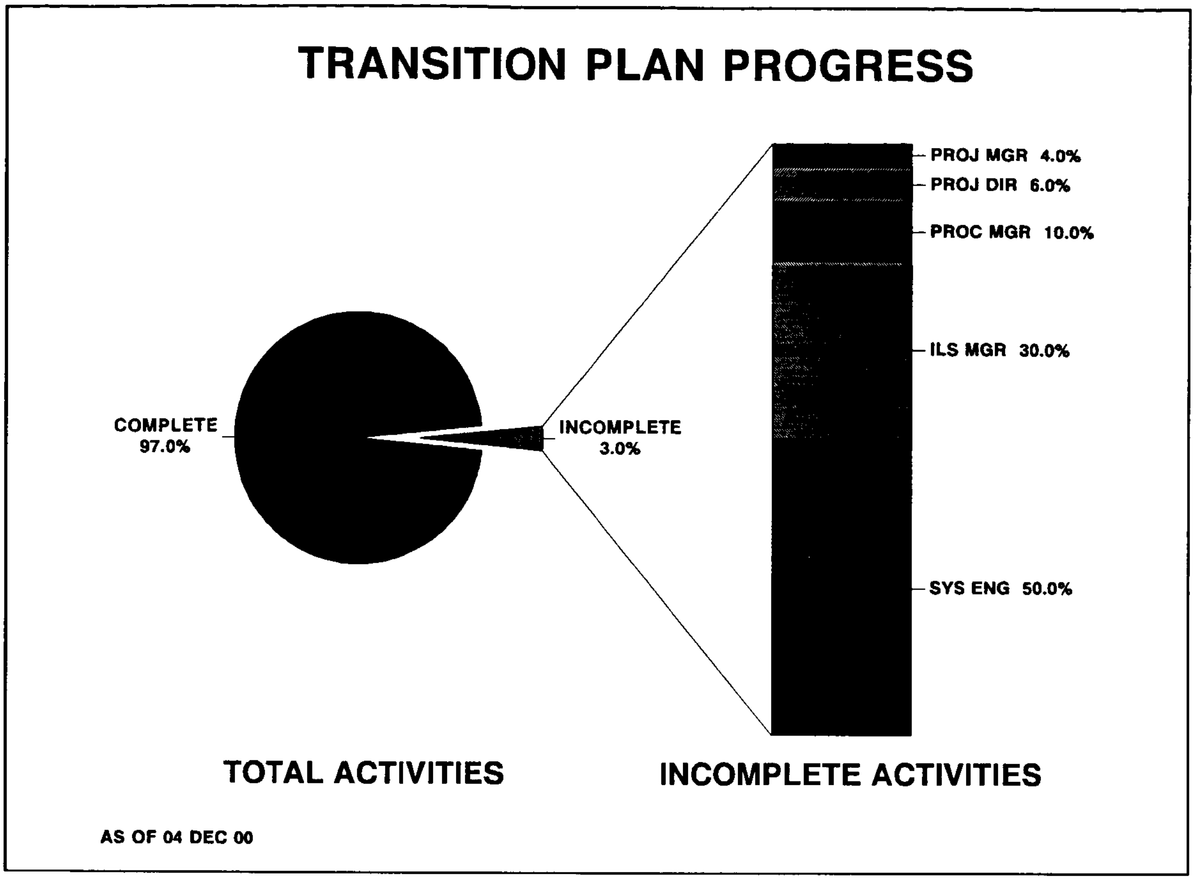

Figure 3 Transition Plan Progress

Today's Training in the High Technology Arena

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Abstract

To keep in tune with the rapidly changing "Hardware" technology, it is imperative that all of the "Supporting" components of a program's efforts reflect these increases in technology. To maintain a work force that keeps in tune with the ever increasing technology base, training needs to remain a major consideration in all types of organizations.

This paper focuses on the area of training and education and suggests a reasonable, cost effective alternative to carrying the entire burden of developing, training and maintaining a workforce in a rapidly changing, highly technological environment.

Introduction

It has been known that one of the most important and costly components of a company's make-up is that of training. With the current state of the economy, it is becoming increasingly more difficult, in terms of time and money to adequately train individuals to perform in today's high tech environments with any degree of competency.

This is even more imperative when one looks at the mission of organizations such as government. The government has a requirement to maintain a highly trained workforce for internal operations and, due to downsizing, incurred a requirement to take on work previously handled by contractors and consultants.

In a large number of organizations, be they commercial or government contractors, training/education was seen as a "necessity"; however, during lean times, the training of individuals is often one of the first areas to be drastically scaled back, with even whole departments being eliminated.

Today, to reduce operating costs within the government arena, we are seeing more and more jobs, that were considered contractor jobs, being performed by government personnel. These jobs range from office support to highly skilled, engineering related.

With earlier technology, it was possible to "Develop" individuals based upon the experience of the senior members of the organization. The scenario within the government area is that some of the jobs being taken over were not performed by government employees. Therefore, "senior personnel" are not becoming trainers of the junior personnel. Add on to this the fact that training is rapidly becoming more costly and, due to rapidly advancing high technology, even the senior level personnel have requirements to be trained.

Current technology is software intensive, the amount of code written to operate and support current systems has increased geometrically. Space systems being developed require "training" over and above current practices. We are in a high technology environment, the computers and machines of ten years ago have grown in technology by leaps and bounds.

Customers of high technology systems realize that the training, needed to support the system is very costly and that they are becoming more actively involved in operational aspects of the systems; therefore, the customer workforce needs to reach the level of maturity that the contractor's personnel are at. This will allow for a smoother transitioning period to occur.

Reason For Training

The following represents three (3) reasons why training is needed:

1. Program requirement. This is found on the majority of high technology government contracts. The contractor develops the product, and since the customer probably has no experience with the piece of hardware, operator and maintainer training is required to support the equipment. The cost of the training development is borne by the customer and is included as a line item in the contract.

2. Purchase of a new piece of hardware and/or software for conducting day to day business. Here the company has purchased hardware or software for achieving the goals of the organization in a hopefully more competitive and/or cost effective manner. The cost of training is borne by the organization and will come out of current profits. It is anticipated that this cost will be more than offset by the new process once the personnel are trained and the "new" system is running up to speed. To some extent, this type of training is required to provide support for space operations.

3. Increase the overall skill and knowledge base of the organization. This usually entails allowing the personnel to attend seminars or college to work on a degree or work related courses. This cost comes out of profits and the anticipation is for a happier, well educated work force.

This paper will focus on this last reason. Increasing the skill and knowledge base will certainly assist in bring about a better transition from contractor to customer responsibilities.

Economic Climate

Everyday you can read about some problem in the economy. There is reduced spending money for the organization which results in an organization folding or perhaps a reduction in force (RIF) - layoffs. This is becoming even more prevalent in the government sector. Criticisms abound with paying a government worker and a contractor to "work the same job". This is part of the reason for transferring more of the jobs from contractor to government worker it represents an attempt to reduce operating costs.

Now a rather large decision needs to be made, what jobs are to be transitioned?. There can be a large learning curve involved with the higher technology tasks. In the meantime, however; the *support* type work can be transitioned over in a phased approach. It needs to be kept in mind that if not done correctly, more labor could be required to keep from missing deadlines (and possible loss of equipment, life and budget.

Even with transitioning those tasks that are considered mundane, there exists a requirement for training personnel.

The following questions now come to mind - what type of training is needed?, how do the existing personnel get the training to keep up with existing technology and do the job?, where is the training to come from?

First we need to look at the type of training that can be involved.

Training Types

There are four (4) basic types of training that will be addressed and these include:

In-House Training

In-house training is controlled by the internal training department. Here the organization must maintain the training department and all necessary support personnel (administrative support, training developer, instructors.)

Advantage: training courses can easily be developed and geared to a particular organization's way of doing business. Personnel have knowledge of the organization's policies and work load and can minimize the amount of time needed to "rack the brains" of the in-house experts (knowledgeable users) specifics on requirements.

Disadvantage: in tough economic times, this department has large cuts or is eliminated totally. Additionally, Training personnel need to keep up with advances in technology and revise material, if the department is reduced, who will do this?

In the case where government personnel are to perform jobs previously done exclusively by contractor personnel, the contractor is the organization with the "in-house experts". The government will need to receive assistance from the contractor.

Therefore, in-house development would be utilized for the support type functions and job assignments.

Seminars

Seminars are defined here as those instructional courses that are given off-site of an organization. Advantage: normally the material being delivered is kept up with current advances in technology. In good economic times, seminars are very good for keeping your personnel current with advances in technology. There are limitations as to the type of courses that can be offered. Seminars are usually limited to type of technology, not with specifics. For example, a seminar on how radar works not a specific radar system.

Disadvantage: This type of training can be extremely expensive. For a 30 hour seminar it can typically cost $1,200 to $1,400 per person. This does not include travel, room and board. The employee will not be accomplishing any work during the time of the training.

Consultants

Consultants can provide the needed guidance in developing training for use by an organization.

Advantage: Consultants are experts in their line of work and are normally well versed in extracting information needed to develop training and incorporating the organization's policies and practices.

Disadvantage: Consultants, unless they are subject matter experts in your organization's way of doing business, will need to interrupt employees during their research. Consultants can also cost a lot of money, - money that is not readily available in today's economic climate. Typical costs are $2,000 a day (plus expenses).

Traditional Institutions

Here we will consider the local college. In order to stay competitive and increase enrollment, are developing state of the art training facilities. They are not just looking at recent high school graduates but personnel in the work force.

Advantage: Relatively low cost to the employer. Provides relatively current and up to date technology, though not as quick as consultants or seminars. This has to do with the process involved in establishing or revamping a course. Since the majority of courses are given at night, the employee is available for completing normal work assignments.

Disadvantage: Cost for establishing a new training facility usually not in the "Budget". Remember, colleges also feel the impact of the economic climate.

Training Alternatives

It is acknowledged that to remain a viable, effective organization in today's high technology environment, it is imperative that the work force remains trained. This also holds true if one wishes to transition work from one type of organization to another (contractor to government).

There are numerous alternative ways of accomplishing this training. The focus will be on three (3) "High Tech" ways: computer-based training, interactive video, and long distance learning.

Computer Based Training

Computer-based training is utilization of a computer for direct interaction with the student presenting lesson content, providing practice and testing student progress.

Due to the flexibility an capability possessed by the computer to provide branching instructions, the computer can become an infinitely patient tutor. Computers can also be used to control other media and to provide students with necessary reference materials, performance aids, and simulate environmental or laboratory facilities.

Successful computer-based instruction depends upon the proper mix of instructional content and methods delivered by an adequate delivery system. This is accomplished by conducting a thorough analysis of instructional requirements as well as the commitment of time and resources to produce quality training programs (and not a page turner).

Computers utilize a variety of different interactive terminals or combine other media (i.e. video) to present individualized instruction. Students may be shown or placed in highly simulated environments by combining computer capabilities in conjunction with other media or equipment for purposes of instruction or testing.

A large number of an organization's computing hardware will suffice for the running of computer-based instruction, thereby reducing some of the acquisition costs.

The major cost would be that of development. There are a number of software courses available for purchase that may be helpful in the training of some support type jobs.

Advantage: For today's problem, training in-house personnel with reduced spending a form computer based training offers a good alternative. A larger number of persons are able to be trained with minimum employee downtime.

Disadvantage: Few developers of Computer Based instruction are aware of certain requirements when developing this form of training, as a result, CBI was known as a "page turner" and a very costly one. Computer-based development costs can range from 50 to 500 hours of development time to produce 1 hour of student classroom time.

Where large numbers of students are to be taught and/or annual participation is required, computer-based training can be effective.

Interactive Video

This type of training offers realistic type of training and can simulate the actual work scenario. Flight simulators utilize this technology.

Advantage: This is very useful for training people where one mistake can result in the loss of money and lives. Or where there is one piece of unique equipment and training equipment is not feasible. An example of this is the current Space Station program.

The Space Station program will utilize interactive video with long distance learning. Astronauts will be able to read the text and watch a demonstration of a maintenance task by a diver (neutral buoyancy) while performing the task. This is accomplished by means of uplink/downlink capability (this is taking long distance learning one step further).

Disadvantage: To come up with an hour of training time (using interactive video) it would not be outlandish to spend 800 hours in development time.

Long Distance Learning

This provides instruction to many people in many different locales. Long distance learning can be accomplished by television or by modem, with computer based instruction. A common form of long distance learning is television courses. Here the student can receive all the information that the students in the class are exposed to.

This type of medium can provide two-way communication with the instructor, which allows for interaction among all "class sites".

No matter which of the "High Tech" delivery systems that are employed, it is important to recognize that a type cost versus benefit analysis is mandatory.

Additionally, it is important to remember that not all training situations lend themselves to the aforementioned three ("high tech" methodologies.

Our original question was to find a feasible solution to develop and maintain a trained work force. If we are currently looking at training large numbers of personnel with reduced costs there are two (2) methodologies to consider.

Problem

To develop and maintain a skilled and knowledgeable work force even during a bad economic climate. Of all the scenarios presented, what viable solution or solutions are available?

Solution

The following addresses two (2) plausible solutions that are available and can work.

In-House Training

In the situation where the organization has need of training all its personnel in the use of standard office software, computer based training has been used successfully.

The typical training scenario has a set schedule for the training class, a limited number of students that can effectively be taught per session. Due to the fact that the classes are held during working hours, no shows are typical. Also, the computer experience of the students are typically wide in range, resulting in some individuals being bored, some learning and some lost. To offset this, the course would need to be taught at three (3) different skill levels. This would further reduce the number of students actually taking courses at any one time.

With computer based instruction, the course consists of program files, student work files and student manual. Once written, it costs next to nothing to make copies. The make-up of the course can be such as to incorporate all three skill levels. People can set the schedule for completing the course to those times when their work load is lessened. The student manual provides a reference book for those situations when the individual needs to refresh how to accomplish something.

One organization, uses video in conjunction with computer based instruction for teaching office software. The result was four (4) times as many students were taught in the same time frame as previously taught using traditional in class training. Specific Computer-based courses have been developed and employed for courses that are recurring in nature (mandatory annual recertification).

Traditional Institutions (Cooperative Venture)

The following is a solution that allows organizations to maintain skilled and knowledgeable personnel. Previously, it was brought out that in times of tight money, training suffers. The requirement for maintaining a skilled labor pool still remains.

The problem is - *How can organizations maintain this labor pool?* By cooperative venture with the local college. In this scenario, commercial organizations can get together with the college and pool resources.

Instead of each organization building a state of the art training facility, at each individual site, maintaining the facility, developing the courses, and maintaining a large training staff this is done at a central location - namely the college.

This cooperative provides many benefits: (1) the cost of the facility is shared by the members of the cooperative, (2) the labs are available to the employees of the cooperative, (3) the college receives a potential increase in student enrollment, (4) commercial organization with training at a reasonable cost, the cost of a college course is substantially less expensive than any alternative form of training, (5) the commercial organization gets trained personnel in utilizing state of the art equipment, (6) knowledgeable instructor can gear course to individual organization's way of doing business (provide examples of how to use the information).

An example of this alternative is Brevard Community College (BCC) in Cocoa, Florida. Situated in the Space Coast of Florida, BCC has numerous technology programs. For example, Within BCC's Institute for Space Technology there is a Logistics Technology program that offers an Associates of Science degree in Logistics Technology; Hazardous Materials; Quality Assurance; Space Engineering. Within this program there are courses that, are competitive to seminars and provide an inexpensive alternative.

For example a seminar on LSA/LSAR ranges from $1295 to $1,400 for 30 hours worth of training and give continuing education credits. BCC has an LSA/LSAR course that is 48 hours in length and gives 3 college credits and all for $105.

	SEMINAR	BCC COURSE
LENGTH	30 HOURS	48 HOURS
COST SEMINAR	$1,295	$105
ROOM/BOARD	VARIES	NONE
AIR	VARIES	NONE
CREDITS	@3 CONTINUING	3 COLLEGE

The above chart shows the potential benefits accrued by adopting the cooperative venture There is 60% more class time and 1133% savings in cost of the seminar per person. This does not include the savings in the other expenses.

BCC recently completed building a state of the art technology facility including a computer lab with current releases of engineering software, and other forms of multi-media equipment.

BCC, as do other educational institutions, are able to set up degree programs on the client site. A number of colleges in the area of Kennedy Space Center offer varying degree programs, as well as individual courses, for the specific purpose of satisfying educational requirements of Kennedy Space Center and do quite well.

This demonstrates what can be accomplished by joining together as a team. Not all cooperatives would be set up exactly the same; however, the bottom line is that industry and educational institutions need to work together to survive and prosper in today's rapidly changing high technology environment.

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THE THIRD KIND OF LOGISTICIAN

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Abstract

Technological advances during and since World War II have created complications to the effective accomplishment of logistics functions. These complications are due to the added functional areas required for effective support as well as to the increased sophistication required for logisticians. This paper identifies the backgrounds of past and current logisticians and makes recommendations for the educational and technical background of future, effective logisticians.

Definition

Historically "logistics" was defined as:

"*Management Operations and Technology associated with the time and place utility of men and materials*".

This definition in the days of simpler technology, resolved itself into the provision of supplies where and when needed. Even when Hannibal crossed the Alps to invade ancient Rome, his primary concern in making the treacherous journey was to keep his troops fed, his elephants comfortable, and all healthy so that they could be effective fighters. Consequently logistics primarily meant "supply" and this philosophy was sustained up to and through World War II.

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The First Kind

During World War II all able-bodied men were called into the military services, in effect draining the universities of males. The government recognizing this dilemma, and, to keep the university operational, created programs whereby young men were returned to the university in uniform to study various relevant areas, one being inventory, warehousing, and distribution. Colleges of Business picked up on this and recognized a profitable area of instruction where industrial companies employed these graduates, and faculty could research, develop, and further improve this approach to logistics.

Heskett et al (1) from this perspective defined logistics as:

"The management of all activities which facilitate movement and the coordination of supply and demand.

Notice the emphasis on supply and movement.

- Principles of Management
- Marketing
- Accounting
- Finance
- Economics
- Operations Management
- Quantitative Methods

Table 1: Basic Core Content of the Business Administration Degree.

Table 1 indicates the basic areas of

instruction for this first kind of logistician while Table 2 shows the specialty or "option" areas for this type of background.

- Warehousing
- Materials Handling
- Packaging
- Traffic and Transportation
- Inventory Control
- Order processing
- Information Flow/Systems
- Customer Service

Table 2: Specialties for the logistician of the first kind.

A recent survey (2) indicates that:

most Colleges of Business Administration generally follows this type of content; some even specializing their degree requirement further (i.e degrees in Transportation).

The Second Kind

Colleges of Engineering currently produce the second kind of logistician. In the engineer's education emphasis is placed on scientific knowledge and technical performance and generally, when time permits in the curriculum, a rudimentary understanding of the necessity for deployment (or distribution) operations and retirement of the equipment is studied
Historical precedent is so strong that even where the word "logistics" is used it generally refers to distribution and inventory handling, ignoring the lessons learned since World War II.

Table 3 indicates the general academic content of the most current engineering degrees.

- Mathematics/Statistics
- Chemistry
- Physics
- Systems Engineering/Management
- Human Factors
- Information Systems/Computer Science
- Scientific and Engineering Disciplines
- Economics

Table 3: Degree content for Logisticians of the Second kind.

While some engineering degrees offer the technical knowledge required to become effective logisticians, they do not relate this knowledge to what actually occurs in the "real world" to smoothly transition through the phases in the equipment's life cycle, dealing with equipment performance.

The Third Kind

During World War II it became evident that the deployment of thousands of copies of complex equipment could not be adequately supported by traditional methods of supply. By the time this was recognized it was late 1944 and there were strong indications that the U.S. and its allies would win the war. Further, the disruption to ongoing operations from major organizational changes was considered too risky to the total war effort so that the decision was made to reorganize after the war was won and demobilization had occurred.

The famous Boeing B-17 "Flying Fortress" nicely illustrates the problem. There were literally hundreds of B-17's sent to the European theater and the Pacific Theater. Each airplane had ten crewman requiring training that ranged from two years in length to six months. In addition, technical support people, equipment, and facilities had to be provided to sustain an effective force. Now, when one multiplies this effort by literally hundreds of different total systems - some larger and some smaller than the B-17 aircraft, an indication of the complexity of the problem is achieved - and it became obvious that a new philosophy of support was needed to effectively use the national resources. This led to the logisticians of the third kind.

In the early 1950's the first documents defining a "Systems Management" approach to the development of technological systems emerged from newly formed Department of Defense. This documentation led to the definition of a "System Engineering" methodology which in turn changed the meaning of logistics from a "Supply" emphasis to the broader "Support" definition (3). Now the logistician had to be capable of meeting the ever increasing dependence on high technology aids to solve increasingly large and complex problems in the logistics domain in order to meet the requirements of logistics as defined in DOD Directive 100.35G (3):

"... A composite of the elements necessary to assure the effective and economical support of a system or equipment at all levels of maintenance for its programmed life cycle."

Six years later in 1974, after much debate, the Society of Logistics Engineers defined logistics as:

"... The art and science of management, engineering and technical activities concerned with requirements, design, and supplying and maintaining resources to support objectives, plans and operations" (4).

Table 4 lists the major disciplines now included under the logistics umbrella, showing clearly that supply alone is far from adequate even on a conceptual basis:

- Reliability
- Maintainability
- Maintenance Planning
- Support and Test Equipment
- Supply Support
- Packaging, Handling, Shipping & Transportation
- Operations and Maintenance Instruction
- Facilities
- Personnel and Training
- Computer Facility
- Funding
- Management Data

Table 4: Elements of integrated Logistics Support (ILS).

These elements have been modified or added to reflect current technical needs and capabilities.

The scope of ILS is more aptly pictured in figure 1 where the X dimension represents management requirements, the Z dimension is the ILS elements, and the Y dimension is the life cycle. Consequently when pictured in this manner, the complexities of providing adequate support to a large scale, complex system can be more clearly seen. In general the first kind of logisticians, coming from Colleges of Business Administration comprehend, more or less, the XY plane (Systems Management), while logisticians, when they exist at all, coming from Engineering Colleges are represented by the

YZ plane. What is needed for now and the fore seeable future are individuals who are competent in all three, XYZ, dimensions. These will be our future logistics leaders.

Long Term Requirements:

College of Business Administration:

The following are considered the long term requirements for logisticians coming from colleges of Business:

1. Increased awareness between the activities in the management of the firm and the integrated logistics support elements.

2. Expansion of Systems Management awareness to include the notion of the life cycle phases and associated support requirements.

College of Engineering:

1. Integration of Life Cycle awareness and requirements into engineering design instruction.

2. Similarities and differences in life cycle requirements for macro and micro systems.

3. Improved awareness of the physical distribution environment for all engineering disciplines (not just Industrial Engineers).

Short Term Requirements:

College of Business Administration:

The following are considered the important short term requirement for college of Business Administration:

1. Introduction of the notion of product or system life cycle and the attendant development decision structure with its implications for logistics.

2. Continued emphasis of operations management and physical distribution topics.

College of Engineering:

Colleges of engineering should enhance the notions of systems engineering and life cycle requirements while clarifying the semantics of logistics in Industrial, Electrical, Mechanical, Civil, and Chemical Engineering programs.

Conclusions

1. While government and military systems have maintained their currency with logistics changes, most of business and industry has not - and considerable performance enhancements are currently not being achieved as a result.

2. College of Business and/or Management need to reinforce the understanding that their graduates focus on logistics requirements emanating from the design phases thus requiring them to satisfy, or do the best they can with what comes comes out of the engineering phase.

Hence they should become involved in design activities.

3. College of Engineering needs to foster the comprehension that equipment performance needs to be sustained in the field and if the equipment cannot be supported or maintained performance in an ideal environment is useless.

4. The Logisticians of the Third Kind will be the Project leaders of tomorrow and the leaders of industry!

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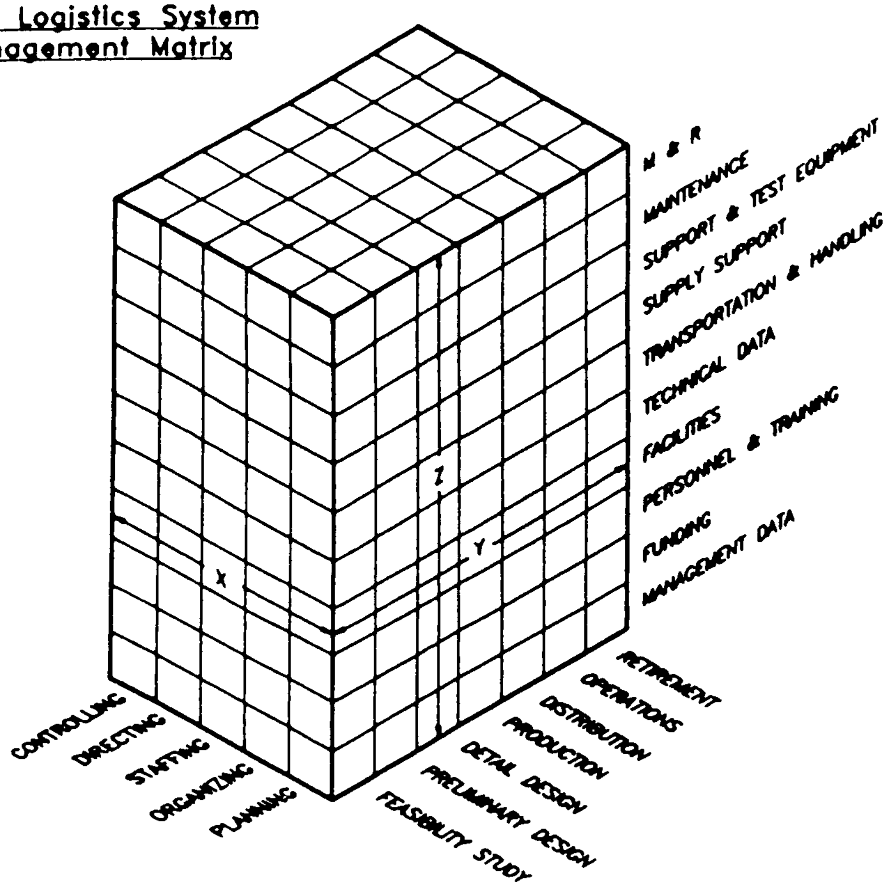
Figure 1: The Logistics System Management Matrix



CONTINUAL IMPROVEMENT IN SHUTTLE LOGISTICS

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Abstract

It has been said that Continual Improvement (CI) is difficult to apply to service oriented functions, especially in a government agency such as NASA. However, a constrained budget and increasing requirements are a way of life at NASA Kennedy Space Center (KSC), making it a natural environment for the application of Continual Improvement tools and techniques. This paper describes how KSC, and specifically the Space Shuttle Logistics Project, a key contributor to KSC's mission, has embraced the Continual Improvement management approach as a means of achieving its strategic goals and objectives. An overview of how the KSC Space Shuttle Logistics Project has structured its Continual Improvement effort and examples of some of the initiatives are provided.

Introduction

The 1994 KSC Strategic Plan challenges KSC to provide safe and efficient space vehicle launch and landing, and payload preparation services while reducing costs center-wide. The Space Shuttle Logistics Project plays an important role in the pursuit of this goal. It is responsible for providing functional flight and ground support equipment (GSE) assets to the Shuttle Program in support of shuttle processing at KSC. These assets are obtained either through the purchase or manufacture of new hardware, or by repair of existing assets. KSC's prime contractor for orbiter logistics is Rockwell International Corporation. Rockwell accomplishes the procurement, manufacture, or repair of assets either through subcontracts with the Original Equipment Manufacturers (OEM), other vendors, or at the NASA Shuttle Logistics Depot (NSLD) in Cape Canaveral. Rockwell also operates the Thermal Protection System (TPS) Facility at KSC. KSC's prime contractor for shuttle processing is Lockheed Space Operations Company. Lockheed is responsible for stocking, storing and issuing flight hardware which is provided by the Shuttle Project elements. They are also responsible for providing spares, repair and off-line maintenance for ground support equipment (GSE) and facility systems used in shuttle processing.

How Continual Improvement Works at KSC

KSC initially adopted the Continual Improvement management approach in 1991. Since that time, KSC has made great progress toward becoming a quality management organization. In 1994 and 1995 NASA KSC was selected as a finalist in the President's Quality Award Program conducted by the Federal Quality Institute. This award program recognizes federal government organizations that have implemented quality management and achieved high levels of customer satisfaction.

KSC's approach to CI features both top-down and bottom-up aspects. A KSC Continual Improvement Plan was published in 1994. This plan establishes the framework by which KSC can balance the original employee driven CI efforts with that of a management driven approach. Not only are employees encouraged to identify and implement process improvements in their own work areas, but each organization's management is challenged to select processes critical to the successful performance of their organization. Teams are established to evaluate these processes using the CI tools and techniques such as process analysis through flow charting, establishment of baseline measurements, identification and implementation of improvements and continual performance monitoring. Candidate critical processes for such improvement scrutiny are identified at the directorate level and presented to the KSC CI Steering Committee for approval. This senior management review assures consistency with the KSC strategic goals and the CI efforts of other KSC organizations.

The Shuttle Logistics Project abides by the CI strategies of the KSC CI Plan. Shuttle Logistics has found that integrated process improvement teams which include representation from both NASA and the contractor are most beneficial. Several successful initiatives also included personnel from other NASA centers such as Johnson Space Center (JSC). Just some of the many CI initiatives conducted by the Shuttle Logistics Project follow.

Continual Improvement Success Stories

Direct Buy Initiative

Procurement of spare parts for orbiter processing and for establishing repair part inventories at the vendor or the repair facility is a key process within the KSC Shuttle Logistics Project. An investigation into this procurement process resulted in a very successful improvement initiative known as the Direct Buy Program. The purpose of the Direct Buy Program is to reduce spares costs through purchase of parts directly from the actual manufacturer when there is no unique added value provided by the subcontractor of the next higher assembly. This reduces the procurement lead time as well as eliminating redundant tasks in several areas such as procurement administration, receiving inspection and engineering.

Since it is essential to maintain the integrity of the systems and equipment in which direct procured parts are to be used, the Direct Buy Program itself involves a process. The Logistics function initially screens for repetitive procurements and projects direct buy savings potential for each spares candidate. The screened items include Line Replaceable Units (LRU's), Shop Replaceable Units (SRU's), and piece parts. From this screening, a direct buy spares candidate listing is established. Once direct buy candidates are identified, they are evaluated by an integrated technical team representing Logistics, Engineering, Product Assurance, Reliability, Configuration Management and Material. JSC Subsystem Managers, OEM's and their subcontractors are also represented in this technical review. The team uses a standard criteria to assure direct procurement is the optimum method of acquiring the part. This direct buy analysis includes an evaluation of the technical data availability, currency and ownership; categorization of the part as either specification controlled or commercial; assessment of the value added by the current supplier; evaluation of the design maturity/stability and a cost analysis. Once a direct buy candidate passes all of the technical and financial screening criteria, the approval cycle begins. This approval process involves both KSC Logistics Project Management and JSC Orbiter Project Management.

As in any quality management organization, methods of improving and streamlining the Direct Buy Program candidate selection and approval processes are continually investigated. For example, the mature Direct Buy Program was averaging a process flow time of 45 days from screening efforts to management approval for direct procurement implementation. Analysis of the processing flow reduced this time to less than 25 days.

The Direct Buy Program has already resulted in significant tangible savings and the anticipated cost savings through the life of the Shuttle Program are even greater. Since the Direct Buy Program was implemented in 1991, it has shown a positive return on investment, with program savings (as of June 1994) in excess of $2.7 Million. The projected savings through the life of the Shuttle Program are estimated to be nearly $8 Million. This figure only represents continuing the direct procurement of those items already approved, and does not consider possible savings to be achieved by application of the direct procurement approach to additional candidates or newly designed systems/hardware.

Thermal Protection System (TPS) Initiatives

Each Shuttle Orbiter has approximately 24,000 protective tiles over its outer skin. These tiles, as well as soft-goods, make up the Orbiter's Thermal Protection System (TPS) which protects the orbiter from the heat of re-entry and the cold soak of space. TPS components are manufactured and/or repaired at KSC in the TPS Facility. A team of KSC workers in this facility has undertaken several initiatives which have resulted in, or will result in, significant monetary savings to the Shuttle Program. Of primary significance are the team's efforts related to tile Production Unit (PU) production. PU's are the larger blocks of TPS tile material from which the individual Space Shuttle tiles are machined. In the past, tile PU's have been procured from an outside vendor at an estimated cost of $3,000 per PU.

Flight-certifiable PU's, as well as non-flight PU's, are used in the day to day operations in the TPSF. Non flight tiles are used frequently in testing and as manufacturing aids. The TPSF team developed the capability necessary to manufacture non-flight PU's from recycled silica waste materials. The team's innovation and cost consciousness resulted in refurbishment and adaptation of excessed equipment from KSC and other locations in order to develop this recycling and fabrication capability. No longer using the costly flight-certified PU's for this purpose has resulted in an estimated savings in excess of $500,000 since the initial prototype non-flight PU was completed in 1993.

The team's success in non-flight PU production opened the door to certifying the TPSF for the manufacture of flight-certifiable PU's. KSC has proven that it has the resources, space, and capability to do such manufacturing, and has received Shuttle Program authorization to proceed. All of the raw materials are on hand. KSC is in the process of acquiring all of the necessary equipment, making required facility modifications and finalizing manufacturing specifications. Plans call for the completion of the certification effort by September 30, 1995. Certification of the TPSF for PU production will better facilitate the "just-in-time" manufacture of tiles for replacement during orbiter processing. Additionally, significant Shuttle Program savings will be achieved by not having to procure the PU's from an outside vendor. The team estimates that this savings could be as much as $6.5 Million.

GSE Quick Disconnect (QD) Repair Relocation

In order to ensure the integrity of shuttle flight systems, often the GSE is subject to stringent periodic maintenance requirements. Due to the risk of flight hardware contamination, QD's on the hydrazine servicing carts and the Mobile Launch Platform hydraulic panels require annual refurbishment. Until September of 1993, these QD's were returned to the OEM for this scheduled maintenance. However, escalating costs and lack of responsiveness by the vendor prompted KSC to seek alternative means of accomplishing this task. Lockheed Supportability Analysis initiated an investigation into transitioning the repair site from the OEM to KSC's on-site subcontractor for precision cleaning, Wiltech. This resulted in another integrated team effort including logistics, engineering and the cleaning facility personnel, culminating in an effective transition of the repair site and significant cost savings for the Shuttle Program. The average repair turnaround time at the vendor was 420 days at a cost of $5,300 per QD. On-site QD repair has reduced this turnaround time to 38 days with significantly reduced costs estimated at $1,300 per QD. Cost avoidance of $275, 000 is estimated due to not procuring fifteen additional QD's which would have been necessary in order to continue to support shuttle processing with the excessive repair turnaround time. The annual cost savings of repairing on-site is estimated to be $180,000.

Air Data Transducer Assembly (ADTA)/SRU Repair Process Improvement Team

The ADTA is a subsystem of the Orbiter's Avionics System, which provides guidance, navigation and control information on the movement of the orbiter through the atmosphere. This subsystem senses air pressures related to spacecraft movement through the atmosphere necessary to update navigation state vector in altitude; provide guidance in calculating steering and speed brake commands; update flight control law computations; and provide display of other essential flight parameters to the shuttle commander and pilot.

A concern over the increasing turnaround time for the repair of failed ADTA SRU's prompted the formation of a process improvement team to evaluate and improve the repair process at Allied Signal Controls and Accessories (ASCA) of Tucson, Arizona, the OEM for the ADTA'S. This effort is an excellent example of a supplier striving to assure customer satisfaction by forming a partnership with its immediate and extended customers in an endeavor to reduce the cycle time for repairs without increasing costs. In August 1994 a thirteen member integrated team of NASA (KSC and JSC), Rockwell and Allied Signal personnel was formed to review, analyze and improve the repair process, with particular emphasis placed on reducing the repair cycle time by 50%.

The team's focus is on the repair process for the transducer components of the ADTA. The baselined average repair turnaround time for one transducer is 280 days. The team established a goal of 150 days based on their understanding of process capabilities and support requirements for shuttle orbiter processing. Allied Signal's process improvement/problem solving model, Total Quality through Speed (TQS), is being used in this initiative. This involves a nine step approach to process analysis and improvement. Process input and output boundaries are defined and process flow charts developed. Potential process barriers and root causes of process problems are identified with proposed solutions. As solutions are implemented, the repair turnaround time must continue to be monitored to evaluate the success of the process improvements. The first transducer since the start of this improvement initiative was sent to Allied Signal in late September. At the time of this writing, the team is mid-way through the nine step process.

Make vs. Buy Decision Process Improvement Team

Once it has been determined that a part is needed, a decision is made as to whether or not the part will be manufactured at the NASA Shuttle Logistics Depot (NSLD) or procured from an outside vendor. Ideally, all relevant factors are considered and an optimum decision is made. This make vs. buy decision process was selected as one of the Shuttle Logistics organizations critical processes by KSC management. An integrated team of NASA and Rockwell personnel has been chartered to review and improve this decision process. The team is chartered to document the existing process, define relevant decision factors, take action to streamline and improve the process, and continue to measure the effectiveness of the decision process. At the time of this writing the team is in the initial stages of process definition and analysis.

Shop Floor Data Collection System Initiative

KSC technicians that perform shuttle processing tasks to prepare the vehicle for its next flight could be considered logistics most important customers. The proper parts, materials and tools must be available to the technicians at the proper location and at the scheduled initiation of the task in order to avoid processing delays. The Shop Floor Data Collection System (SFDCS) is an integral part of KSC's Integrated Work Control System (IWCS). The SFDCS is used to collect data on task duration and delay occurrences and durations, for work conducted at the major shuttle processing facilities such as the Orbiter Processing Facilities (OPF), Vehicle Assembly Building (VAB) and the launch pads. As delays are experienced, operations personnel enter this data into the computer system using a specific delay code. The system can be used to provide real-time status of processing activity, but more importantly, the data collected can be used to drive process improvements. Logistics and operations personnel have recently joined together in the evaluation of the data indicating logistics-related delays. At the time of this writing, this effort is just getting underway. There is reason to believe that the data already being collected by operations personnel can provide the Shuttle Logistics Project with an indication of customer satisfaction, as well as pin-point opportunities for improvement in the processes associated with providing parts and materials to the shuttle processing floor.

Conclusion

The KSC Shuttle Logistics Project has been very successful in implementing the Continual Improvement approach to quality management. KSC's Shuttle Logistics Project strives to enhance process performance and ensure customer satisfaction through the use of CI tools and techniques for process analysis, improvement and measurement. Significant monetary savings, greater process effectiveness, and customer/ supplier partnerships have already been realized. Focus on quality management will continue as KSC conducts its complex mission and pursues its ambitious goals with less resources.

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REVITALIZING SPACE OPERATIONS THROUGH TOTAL QUALITY MANAGEMENT

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Abstract

Total Quality Management (TQM), is easily understood, can be implemented in any type of business organization, and works. This can be seen when one stops to realize that TQM has been around quite a long time and is increasingly being embraced by all forms of organizations, both profit and non-profit. It is being recognized that TQM can help an organization continue even in a tough economic climate.

The purpose of this paper is to show the reader what TQM is and how to apply Total Quality in the Space Systems and Management arena.

Introduction

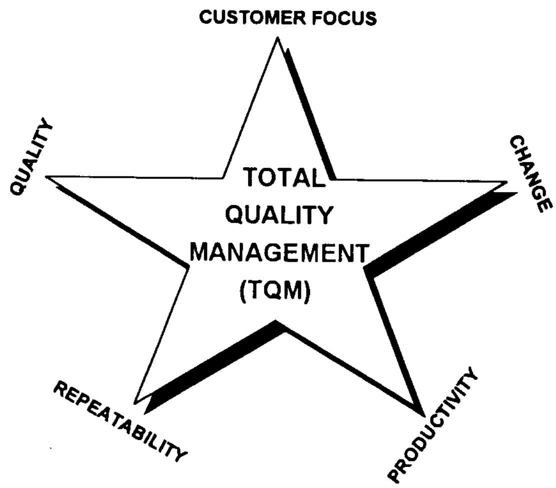
Process Analysis Techniques, Metrics, Baselining, Quality Assessments, Customer Satisfaction Continuous Improvement these are just some of the terms that are associated with Total Quality Management. Throughout recent years, there have been a number of theories or "management techniques" (non TQ) that have surfaced to make "companies better and more profitable".

It seems that the majority of these techniques do not stay around long enough or are not easily adaptable to be utilized by the different type of business organizations. These "non-TQ" techniques are ***developed and implemented*** in high manufacturing, manufacturing environments and are not easily adaptable to other types of environments. TQ on the other hand, is easily adaptable to all forms of organizations.

This paper addresses the following topics and concepts that provide for easy implementation of TQM:

- o Total Quality Management definition
- o Teams and Partnerships
- o Types of Teams
- o Process Analysis Techniques
- o Disciplined Systems and Processes
- o Total Quality Implementation
- o Process Management
- o Baselining
- o Metrics
- o Teaming
- o Quality Assessments
- o Process Flow Charts

What is Total Quality Management?



Total Quality Management consists of (1). Change - Changing paradigms: work smarter not faster, look for process problems and people problems, encourage participative management. (2). Repeatability - Well defined processes, consistency. (3). Productivity - Defined, measured, how can we increase it? (4). Quality - Defined, measured, defect detection then prevention. (5). Customer focus - Everything you do has a customer, are your customer requirements defined? Is your customer satisfied? What are the gaps between what you provide your customer and what they want, or even what they need?

Total Quality - A customer-focused, systematic approach to continuous improvement. It represents a management philosophy that encourages teamwork, joint-problem solving, communication, trust and continuous improvement of products and services. It is known by its use of analytic techniques, particularly statistical methods, to provide an objective reason for process monitoring and change(s).

The main thrust of TQM is in that of Customer Satisfaction. Customer satisfaction deals with delighting you customer. Since an organization is typically exchanging a product or service for money, it is important to remember your obligation to your customer. The customer is the one who defines quality. It is the contractor's responsibility to ensure that the quality of the product or service is meeting and exceeding the customer's needs and expectations.

It is important to recognize who your customer is both internal and external to the organization. To properly understand the customer's needs and expectations, you need to recognize their place in your organization.

Recognizing your customers place in your organization, allows you to determine your customer's needs and expectations.

For example: Lets say an organization has 100 employees, sells 200 widgets a week, orders 1000 items a week and that this is a 90% perfect organization, there would be:

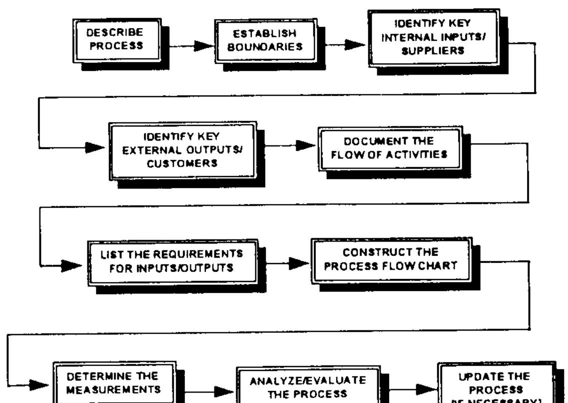
10 employees not paid per week
20 widgets not being delivered on-time

100 items not received a week

It can be easily seen that this 90% perfect organization is unacceptable. There are quite a number of unsatisfied customers.

An expansion of this philosophy is known as Continuous Process Improvement. Continuous Process Improvement is a methodology whereby an organization describes in detail the processes necessary to carry on the organization's business. It assists in "weeding the garden" by identifying short comings in the organization's way of doing business. With the incorporation of a feedback mechanism, it is possible to modify, add and/or delete processes.

CONTINUOUS PROCESS IMPROVEMENT



The "Best in Industry" organizations have embraced and practice Total Quality Management. To help an organization trying to incorporate Total Quality and attaining improvement, it is important that all individuals in the organization learn, accept and practice TQ in order for the transition to work. This includes the development of teams and partnerships. As mentioned previously, no one individual, in an organization, works in a vacuum and does not have any customers.

Teams and Partnerships:

The Total Quality effort within any organization needs to have a structured controlling procedure. This usually takes the form of a [top-level] Executive Steering Committee and continues on through the organization to the lowest levels in the form of subcommittees, and teams. This process allows the organization to address quality related issues at all levels and promotes employee involvement.

The Executive Steering Committee would have the following responsibilities:

o Develop the TQM Implementation Model (these are the steps that are followed to implement TQM)

o Write the plan for attaining TQM which entails writing the strategic objectives necessary to improve the organizations way of doing business this includes identifying organizational goals and objectives based on customer inputs, evolution of the business cycle and employee feedback.

o Be the formal delegation of authority to charter cross-organizational teams.

o Review the status of the TQM implementation process

There can be steering subcommittees at all levels of management, as needed, to assist in formally addressing quality issues at the various levels within the organization. Using the critical processes and identified problem areas as targets for continuous improvement activity, the subcommittees in each department perform tactical planning for total quality improvements.

Operating Levels

This level is comprised of functional groups, individuals and teams conducting TQ activities. The TQ process is worked through the establishment of permanent, temporary, or Ad-Hoc quality improvement teams. Permanent teams known as task teams or integrated product teams (IPT), are cross-functional in nature and are organized to develop and produce specific systems or subsystems. The composition of the IPT leads to an interdisciplinary cooperation that

reduces product development cycle time and defects.

It is important that the steering committees utilize the expertise of the employees at all levels to solve problems and improve work processes.

The Steering Subcommittee is the vehicle for the chartering of process teams who tasks are to identify, define, measure, and improve the organization's critical work processes. Steering subcommittees also monitor teams and report on status.

Types of Teams

Successful teams recognize the need for utilizing a structured approach which includes clearly defined roles and responsibilities of its members. The following delineates categories of TQM team membership:

TQM (Process) Specialist: Supports the team in planning, team methodology, metrics,
TQM training, and team process. Coaches the Team Leader.

Leader/Facilitator: Orchestrates team logistics, presents status, is the focal point for team activities. Steers the discussion ensures the members remain focused on the problem at hand.

Facilitator: Keeps the discussion focused. Controls dominating team members, keeps the leader in charge. Elicits responses from overlooked members. Brings discussions to a close.

Recorder: Records the minutes of the meeting. Can be a permanent or a rotating responsibility,

Member: Contributes ideas and efforts. Works actions.

Process Action Teams - Target a specific process for improvement using a structure methodology that emphasizes baselining, measuring and standardizing.

Development Teams - May address processes or systems that are unclear, poorly documented, or not yet in place.

Tiger teams - These teams solve critical problems needing short term resolution.

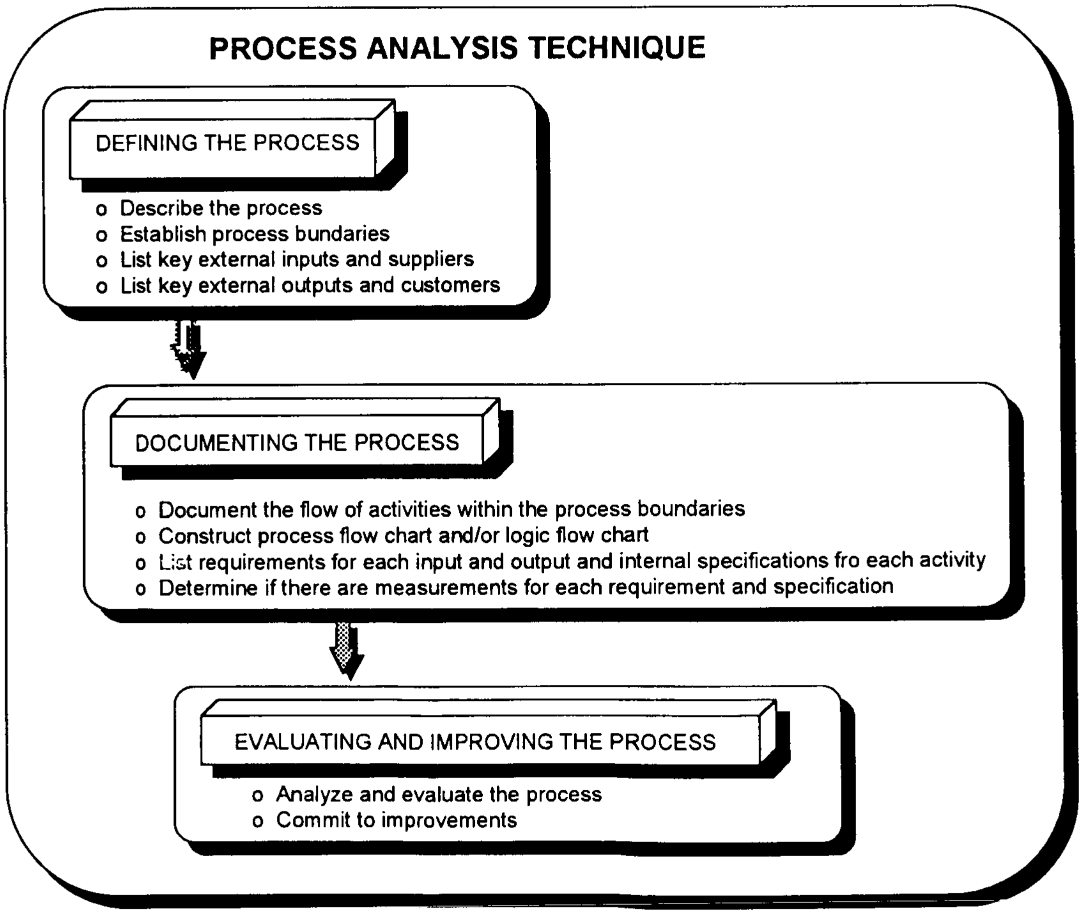
Temporary teams are normally formed and chartered for specific problem-solving or process analysis issues. these teams follow structured TQ approaches that are tailored to enable a team to achieve its charter.

Integrated Product Team - this concept realigns vertical organizational structure centered around functions to horizontal teams focused on specific elements of the product.

Quality Action Teams - composed of employees who are tasked with resolving specific problem areas and issues. This type of team is focused toward achieving feasible solutions, and is disbanded when their charter is fulfilled.

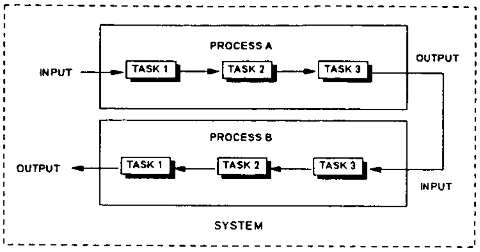
Process Management Team (PMT) - this team addresses much broader issues than quality action team and can have a much longer life.

The Process Analysis Technique is made up of the following:



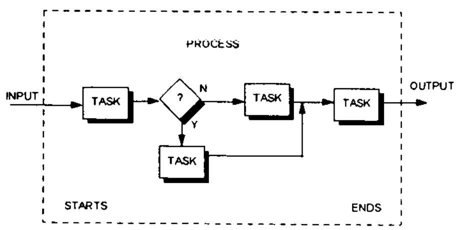
Disciplined Systems and Processes

The organization needs to focus on defining and improving processes. A process is a definable set of tasks which produces measurable outputs. A system is a set of processes that work together to produce a specific output:



A set of processes is known as a system if the processes work together to produce a specific output. Determine what makes of a disciplined system or process.

Identify some critical processes that each functional group within the organization controls that could be improved. Take one of the processes that were identified and list the: Supplier, Input, Output and Customer. Next list (1).. the task that initiates the process, (2). the task that ends the process, and (3). any applicable intermediate tasks:



To improve work processes it is important to:
- o Identify critical processes
- o Baseline (define and measure) critical processes
- o Improve critical processes

It is important to know that Process Improvement is measurable **it has to be to be able to see if its working.**

Process improvement can include:
- o Reducing cycle time
- o Reducing costs (workhours including reducing rework and materials including reducing scrap)
  - o Reducing defects
  - o Meeting schedules
  - o Meeting budgets and estimates

The following represents the common elements of TQM:

1. Management leadership

2. Management style change to encourage employee participation-participative management

3. Focus on customer needs

4. Emphasize process problems and not employee blame

5. Requires prescribed improvement plans

6. Uses statistical methods for process improvement

7. Quality is directly related to productivity and inversely related to cost

Changing Environment:

One of the most difficult things an organization can effect is change. It is known that individuals have a hard time coping with changing the status quo in the work environment. Resistance to change usually rears its ugly head. This is true when the employee feels that change will force that individual to "release information" that was known only to him/her. This interpretation of protecting one's job. So the individual employee ask - Why change?

Change, however, can be very beneficial. In today's economic climate, there are less dollars budgeted for existing programs and future programs. In reaction to this, organizations are attempting to scale down day to day operations while increasing productivity.

The reasons why an organization needs to change is as follows:

- o Competition
- o Budget/Profit
- o Technology
- o Customer Needs
- o Efficiency
- o Development

Competition - with less money available, competition is increasing. We see where large corporations are merging in order to obtain a competitive edge.

Budget/Profit - if an organization is left running "status quo", and less monies are available, it can be seen that profit cannot remain the same. To increase profit - change is eminent.

Technology - the world today is experiencing rapidly changing technologies, it is imperative that, for an organization to remain marketable, that the organization acquire the newer technology in an expeditious manner.

Customer Needs - in years past customers relied on the recommendations of the supplier of products or services, what was given was what not always what was needed. It is important for the supplier to become aware of what the customer needs. Change is warranted in the way the supplier deals with customers.

Efficiency - to remain competitive, an organization needs to increase efficiency. This could mean that the every day processes be reviewed for shortcomings, then either modify or develop new ones.

Development - Expansion of the organization is accomplished through change.

Ever increasing demands from the customer added to ever increasing costs will usually force an organization to one of three alternatives.

1. The organization decides that the increasing demands and expectations of the customer are unreasonable. This results in losing the customer, lost revenue, loss of profits, potential loss of other business with a potential bottom line of the disbanding of the business.

2. Organization could reduce the quality of the products and services in order to reduce costs. This results in losing the customer, lost revenue, loss of profits, loss of other business with an almost assured bottom line of going out of business.

3. The organization could strive to exceed the customer's demands and expectations, and simultaneously lower costs incurred by the organization by improving work processes. This would allow for development of the organization and increases the probability of acquiring more business from existing customers and business from new customers.

Total quality Implementation Approach

Involve the application of TQ principles as an integral part of your day-to-day way of doing business. The type of business the organization engages in will dictate the approach taken to satisfy their unique operational needs and environment. The organization needs to a). identify their customer's top level requirements and expectations for each business area, b) identify the key processes and infrastructure drivers that determine their outcome, and c) develop metrics and closure plans to ensure each of these key processes and drivers are the "Best in Industry"

Process Management

Every supervisor needs to be focused on improving the quality, reducing the cost, and shortening the cycle time of the key processes they manage and support. These efforts need to be in-line with top-level objectives that drive the organization's bottom line and need to be in support of internal and external customer requirements. If your area's output is not directly linked to the organization's business objectives, selection of the process can be based upon one or more of the following criteria:

- The process has the greatest impact on the organization's key customer(s), or,
- The process creates the greatest demand on the organization's resources, or,
- The process is a high priority according to the upper management, or,
- The process most adversely impacts organization's adherence to schedule Individual components need to accomplish the following:
- Define their key process, and identify related customer expectations
- Establish metrics for baselining, benchmarking and improving the performance of their key process
- Set improvement goals, provide the required resources, monitor progress and take actions to achieve the planned improvements
- Gain employee participation and teamwork and partner with both internal and external customers and suppliers by actively solicitating their involvement in process improvement
- Establish process improvement and customer satisfaction goals with employees as part of the performance management and compensation process.

Baselining

At the functional level within the organization, functional components identify all work processes, rank them by criticality and develop flow charts. The flow charts are to delineate the inputs an suppliers, customers and products, process metrics, and cycle time for each process. This information is used as the baseline which is used to analysis any process flow for potential streamlining activities.

Metrics

The top-level operating organization needs to develop and track appropriate metrics on those key processes that support their customer's top-level requirements and expectations for each business area. The metrics should be operational in nature and be predictors of the processes desired outcomes.

Each functional area, in turn, needs to also develop and track the appropriate metrics on those key processes that support your customer's top-level requirements and expectation for their department's mission.

A TQM metric defines the unit in which a characteristic or an attribute of a work process is measured. TQM metrics can be categorized along several dimensions - by what the metric is supposed to measure; by the type of measure (physical nature or units of the metric); by the purpose of the metric.

These metrics need to be displayed so that everyone in the organization have ready access to how the group or operating unit is progressing towards accomplishing its stated objectives and goals.
Top-level reviews by appropriate senior management from the organization are recommended on a monthly basis to assess progress and implement corrective action as necessary.

Identification of suitable metrics within a process is critical to resolving problems. Wrong or irrelevant measures lead to a waste of time in data collection and chasing the wrong problem.

Types of Process Metrics

Productivity- This characteristic deals with measuring units of output per fixed units of inputs (fixed level of effort) It measures how much work is accomplished and is based on a fixed effort. An example would be how many pages of text are completed in a maintenance manual by the first in-process review.

Quality - This characteristic deals with measuring the degree to which a customer's requirements are satisfied. Discrepancies where requirements are not satisfied are used as a quality measure. This type of metric depicts how well a process is working. An example is also in technical publications measuring the number of pages per comment. This provides a measure of rework.

Timeliness - This characteristic deals with the amount if time it takes to complete the various steps of a process, particularly in regard to performance against a schedule or estimated time to completion. This metric addresses the "how prompt" aspect of a process. An example of this would be how many days it takes to get a CDRL deliverable through the review cycle.

Reliability - This characteristic deals with the degree to which a process performs its functions over a stated time period. This metric is based on errors or failures per fixed time. Reliability addresses the "how long does it work" aspect of a process. An example would be the Mean Time Before Failures (MTBF) for a piece of prime mission hardware.

Metrics can be categorized along several dimensions:

- o what is the metric supposed to measure?
- o what is the type of metric?
- o what is the purpose of the metric?

After establishing process metrics, the next step is deciding on the arithmetic category in which the metric data is to be collected. The nature of the metric can usually determine the arithmetic category.

A process metric can be divided into one of two types of categories:

o Attribute data - A metric is classified as an attribute if it represents or is computed directly from categorical data.

TYPES

1) Simple count
2) Classification
3) Percent
4) Ratio or count per

EXAMPLES

1) Number of lines of code written
2) Success or Failure
3) Operational Availability
4) Comments per document page

o Variables data - A metric is classified as a continuous variable if it represents the measurement of a characteristic over a continuum. Processing time can be a continuous variable when measured to a high degree of precision. Types of variable metrics include:

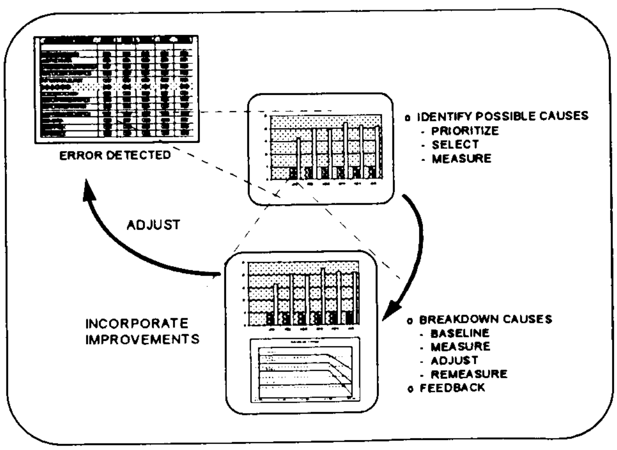
TYPES

1) Continuous measurement of dimensions or time
2) Rates or time rates

EXAMPLES

1) Length, width, height, weight
2) Single lines of code per man-month

HOW DO METRICS WORK?



Metrics depict a pictorial representation of a process, and when designed correctly, provide a feedback that allows for: 1. Error detection, 2. identification of the causes of the error, 3. corrective feedback mechanism, 4. improvement and adjustment capability.

Metrics provide useful information and can be applied very successfully and parallels the effort comprising Continuous Process Improvement.

Teaming

The application of Integrated Product Teams (IPT) is encouraged. Organizational planning should include strategies for IPT implementation and goals. To expand the role of participative leadership, it is advisable to encourage employee participation and involvement in quality improvement teams. Team activities need to be linked to the satisfaction of key business objectives and/or areas critical to the group's mission or charter.

Quality Assessments

The primary responsibility for TQ implementation rests with each functional element. The Total Quality lead provides guidance as to the approach and deployment of the organization's overall total quality strategy. To achieve a common understanding across all functional areas, the oversight process is conducted along three dimensions of approach, deployment and results.

Approach refers to the functional area's leadership action having defined methods for total quality implementation tailored to the unique operational needs and special environment of the organization.

As a minimum, the approach needs to outline the strategy for linking the organization's business goals to every affected manager.

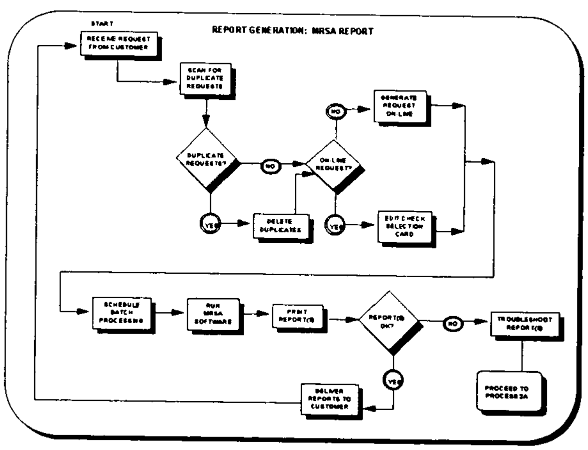
Deployment refers to the communication of the approach to employees with management responsibilities for improving their key processes in the near term and beyond. Results refers to having completed baselining the process being improved and showing process performance trend data.

Process Flow Charts

Flow charts are used to obtain a better understanding of each component of a process and to determine how each component contributes to the process structure. Flow charts depict the overall process better and make it clearer. Flow charts make it easier to identify a problem area(s) contained within a process. They can be used as a training tool to show involved individuals what the process is about. They are used as the vehicle to document the process. Flow charts are used to identify solutions to a problem by modifying the sequence of flow within a process.

Flow charting represents a key component of baselining a process. The flow chart represents a pictorial view of a process and depicts how the process flow takes place. Process flow charts show components (or functions) within a process, the relationship among these components ((or functions) and any precedence. Flow charts depict the steps involved in the process.

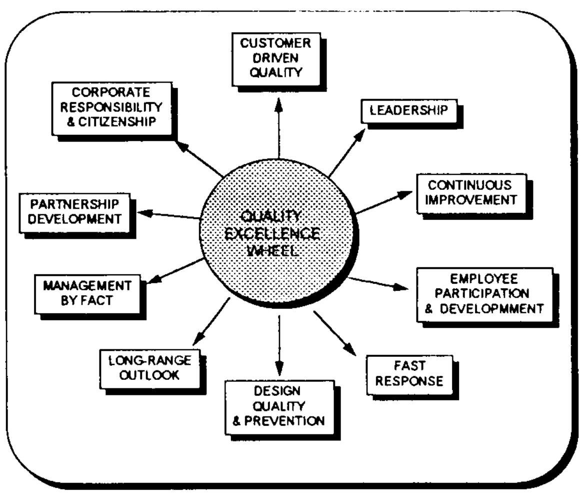
The following is an example of a flow chart for generating a MRSA Output Report.



What wasn't discussed was what to do with all the information that is collected when incorporating TQ. The information becomes a sturdier foundation upon which to build the organization.

This is accomplished by the integration of the overall customer and organization's operational performance requirements.

The following picture, known as a Quality Excellence Wheel, displays a foundational basis for integrating the overall customer and organization's operational performance requirements



Conclusion

It should be noted that TQ has evolved and will continue to evolve as time goes on. It is important to recognize the components that comprise TQ and to use them to their full advantage. It is very important that all individuals in the organization learn, accept and practice TQ in order for it to work.

1. Identify and list your suppliers
2. Identify and list your customers
3. Identify and list your critical processes
4. Prioritize your most critical processes
5. Baseline (define and measure) the most critical processes
6. Get a buy-in from your customer (solicit customer and supplier input and feedback
7. Improve the most critical processes
8. Measure the improvement

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AUTHOR INDEX